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NATIONAL GAS TURBINE ESTABLISHMENT
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MEMORANDUM No. M.261

A REVIEW OF HIGH STRENGTH MATERIALS FOR THE ROTOR BLADING OF HIGH TEMPERATURE AIRCRAFT GAS TURBINES

by

E. GLENNY

FEBRUARY, 1956

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A review and appraisal of data on metals, alloys, ceramics and
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the rotor blading of aircraft gas turbines have been made.   While it is
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wrought or cast, are unlikely to be useful at temperatures above
880°C (on a 100 hour life basis), no other materials immediately
available are likely to replace these alloys for higher temperature
service.   Metallic alloys and cermets possessing similar or superior
strength at higher temperatures have been developed but their inadequacy
in other respects, e.g. lack of oxidation resistance (molybdenum-based
alloys) and mechanical shock resistance (chromium-based alloys and
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M.X.A. 31.1.56

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1.0   Introduction

During the past ten years, the demand in aircraft gas gurbines for greater thrusts (from jet and turbo-jet engines) and higher power outputs (from propellor turbine engines) has stimulated a considerable research effort to provide rotor blade materials that will withstand higher gas temperatures.   In this country, the Nimonic series of alloys has satisfied the requirements for the rotating blading of production engines. In all probability, the recently-developed Nimonic 100 will be used in the immediate future for blades operating at temperatures approaching $900^{\circ}C$ (assuming a 300 hour life).   However, research engineers have designed and tested experimental engines at gas inlet temperatures in the region of $1200^{\circ}C$.   For such operation, the available high temperature high strength alloys must be cooled, e.g. by air cooling, using blades containing internal cooling passages and manufactured by powder metallurgy, extrusion or casting techniques.

While it is not impossible that the further improvements in iron, nickel or cobalt-based alloys (using, for example, vacuum melting instead of air melting, and hot extrusion instead of forging) may yield compositions capable of operation in conventional aircraft gas turbines at rotor blade temperatures approaching $1000^{\circ}C$, it has been evident for some time that there is a temperature limit beyond which alloys based on these three metals will be inapplicable.   Attempts have and are being made to develop new materials that possess similar or higher strength at higher temperatures than existing metallic alloys, and yet will fulfil other performance requirements for rotor blading viz. adequate resistance to creep, fatigue, oxidation, erosion, thermal shock and impact, and satisfactory stability and reliability in the operating temperature range.

The primary requirement is adequate strength at temperature.   As the ability of many materials to maintain their strength at higher temperatures increases with increase in melting point, research workers have considered the usefulness of higher melting materials such as oxides, carbides, nitrides, borides and silicides (all of which may be loosely termed ceramics) and refractory metals such as chromium and molybdenum. Ceramics are characterised by inherent brittleness and high sensitivity to mechanical shock and often to thermal shock, but are resistant to erosion and generally to oxidation.   Metals and alloys usually possess adequate ductility and mechanical shock resistance, but lose their strength at lower temperatures than the ceramics.   The idea of combining ceramics and metals to produce 'cermets' came easily, and considerable effort, particularly in the United States, has been devoted to their development.   A similar effort has been devoted in the United States to the evaluation of the usefulness of molybdenum and its alloys, while substantially less effort has been made to develop chromium-based alloys.   So far the results have been disappointing.   While it is probable that the promise initially indicated for these materials will not be quickly or easily fulfilled, it is too early to take a pessimistic view of the prospects.   Only a small area of the possible fields of endeavour has been developed seriously.

This Memorandum is a review of data on ceramics, cermets, metals and alloys that are in use or have been considered potentially useful for the rotor blading of aircraft gas turbines.   The purpose of the review is to make an appraisal of the relative merits of these materials for this application.   It is mainly concerned with those compositions for which tensile stress-to-rupture properties have been

evaluated and have proved to be similar or superior to Nimonic 90.

2.0   Metals and alloys

Although in this country wrought nickel-based alloys have always been used for the rotor blading of production aircraft gas turbines, both wrought and cast nickel and cobalt-based alloys have been and are being used in the United States.   It is claimed[1] that S 816, a wrought cobalt-based alloy has been the most widely used alloy in recent years in the United States.   However, some engine firms in the United States have recently become more interested in the usefulness of castings for uncooled and cooled rotor blading.

Prior to dealing with individual alloy compositions, the properties of pure metals which might serve as base metals for blading alloys will be considered.   Their melting points, densities and strength properties are given in Table I.   From the stress/density data, it is evident that niobium, tantalum, chromium, molybdenum, tungsten, rhodium and iridium are potentially useful.   Rhodium and iridium can be excluded from further consideration because of their extremely small natural resources and exceedingly high cost.   Of the remaining metals, only chromium does not require protection against oxidation.   Chromium possesses an attractive strength-to-weight ratio, but can be prepared in a ductile state only if stringent precautions are taken to eliminate detrimental impurities such as nitrogen.   All chromium-based alloys so far prepared[4,5], have been brittle, but the Aeronautical Research Labs., Melbourne, consider[6] that the production of ductile alloys is possible.   However, it has yet to be demonstrated that such ductile alloys do not become embrittled by absorption of nitrogen at elevated temperatures.   Niobium has a favourable strength-to-weight ratio and is also ductile, but lacks resistance to oxidation.   The high densities of tungsten and tantalum are disadvantageous from engine weight considerations.   Tungsten and molybdenum oxidise rapidly above 550°C; molybdenum trioxide is volatile above 700°C.

Molybdenum has been a greater attraction to the engine designer than any other refractory metal, because of its adequate natural resources, good strength-to-weight ratio, and relatively low thermal expansion and high thermal conductivity (hence potentially high resistance to thermal shock).   Over three million dollars have already been spent in the United States on research and development work to evaluate the properties of molybdenum and its alloys and to devise methods of protection against oxidation.   As the latter could not be achieved by alloying, protective coatings have been investigated[8] but to date the required resistance to cyclic heating and cooling with superimposed tensile stress has not been obtained.   Also, as for chromium, very small amounts of impurities have been found to exercise a considerable effect on the level and uniformity of creep and fatigue properties and on the recrystallisation temperature; hence very close control of the casting and fabrication processes is essential.   Molybdenum, like some ferrous alloys, displays a so-called transition temperature below which a change from ductile to brittle behaviour takes place.   Oxygen, and to a lesser extent, carbon, have been found to be the primary causes of room temperature brittleness.

Published data on metals and alloys possessing comparable or superior stress-to-rupture properties to Nimonic 90 above 800°C are given in Tables II to X.

The nominal chemical compositions of wrought and cast iron-, nickel- and cobalt-based alloys, and sintered Vitallium (as used in the experimental air cooled 117 turbine at the N.G.T.E.) are given in Table II. (For chemical symbols of the considered elements and compounds, see Appendix I.) Most of the alloys are commercially available but some have only been tested in the laboratory or in experimental engines and are therefore designated "Experimental" in Table III which also includes the heat treatment conditions used to develop optimum high temperature strength properties. The International Nickel Co. alloys, Inconel X550, Inco 739 and Inco 700 are fairly similar in composition (see Table II) to the Mond Nickel Co. alloys, Nimonic 90, 95 and 100 respectively, the high temperature strength being mainly obtained by the precipitation hardening conferred by Ti/Al compounds. Of the three American alloys, only Inco 700 contains cobalt. The American S 616 and British G 32 alloys also have near-similar chemical compositions. The cast cobalt-based alloys were derived from the cobalt/chromium/molybdenum alloy, Vitallium. In order to improve the high temperature strength properties, nickel was substituted for some of the cobalt (422-19), tungsten replaced molybdenum (X40 and H.S.36) and small additions of tantalum were made (73J, 111VT2-2, and 100 NT2). The British G 34 alloy contains vanadium and niobium (absent from the American alloys), and is a high carbon version of G 32.

The densities and available data on thermal expansion and thermal conductivity of the above alloys and also of two cast chromium-based alloys and five refractory metals are given in Table IV. The densities of the iron, nickel- and cobalt-based alloys are all similar (with the exception of X40 and H.S.36), as also are their thermal expansions and conductivities. The chromium-based alloys are somewhat less dense, even though they contain 15/25 per cent molybdenum (specific gravity 10.2), and their mean thermal expansions are only about 50 per cent of the above alloys. The attractive thermal properties of both molybdenum and tungsten are evident from the tabulated data.

Table V gives the values at room and elevated temperatures of tensile strength and Young's Modulus for the materials listed in Table IV.

The tensile rupture strengths for 10, 100 and 300 hours at 816°, 871°, 982° and $1093^{\circ}C$ of the metals and alloys previously considered are listed in Table VI. For ease of comparison, the 100 hour data at $871^{\circ}C$ and $982^{\circ}C$ are presented in the form of histograms in Figures 1 and 2. Stress/temperature curves are shown in Figures 3-5. The most striking feature of the data is that at $982^{\circ}C$, the strongest of the nickel-, cobalt- and iron-based alloys has a 100 hour rupture strength of only slightly over 6 tons/sq.in. The best wrought Ni-based alloys have similar rupture strengths at $871^{\circ}C$ to the best cast Co-based alloys but are decidedly inferior at $982^{\circ}C$. It is characteristic of wrought nickel-based alloys that they show a more pronounced loss of strength with increasing temperature than do cast cobalt-based alloys or some wrought iron-based alloys (compare Nimonic 100 with G 42B and X40 in Figures 3 and 4 respectively). As expected from their near-similar compositions, Inconel X550, Inco 739 and Inco 700 possess similar stress-to-rupture properties to Nimonic 90, 95 and 100 respectively. The nickel-based casting alloy GMR235 has similar rupture strength properties to the best of the cast cobalt-based alloys. Considering the experimental alloys, it is at once apparent that the cast chromium-based alloy containing 15 per cent Fe and 25 per cent Mo has a greater 100 hour rupture strength at $871^{\circ}C$ than any of the foregoing alloys. Unfortunately

no data is available at higher test temperatures. No stress-to-rupture properties are available for G.E.C. carbon-free sintered Vitallium above 750°C, but at this temperature its 100 hour rupture strength is about 80 per cent that of cast Haynes Stellite Alloy No.23, which has a similar composition except for a carbon content of 0.35/0.50 per cent. The absence of carbon is the main reason for the relatively low strength of the sintered alloy. Stress relieved vacuum-tested molybdenum is superior in rupture strength at and above 871°C to any of the nickel, cobalt or iron-based alloys considered. Small alloying additions create considerable improvements in strength, the 100 hour rupture properties of the 0.45 per cent titanium alloy being extremely high relative to unalloyed molybdenum. (See Table VI and Figure 5). The effect is qualitatively explained as being due to the considerable rise in the recrystallisation temperature promoted by the addition of a small percentage of the alloying element. Fully recrystallised molybdenum and its alloys are appreciably inferior in rupture strength properties to the stress-relieved materials. The rupture strength properties of niobium are superior to fully recrystallised molybdenum but inferior to stress-relieved molybdenum.

As the tensile stresses in the rotor blading are centrifugal in origin, the performance of materials is only compared effectively on a strength-to-weight basis, or relative to the current British rotor blading alloy, Nimonic 90. The specific* 100 hour rupture strength data for metals and alloys are given in Table VII. On this basis, Nimonic 100 is now slightly superior in 100 hour/871°C rupture strength to the best cobalt-based alloys. As the majority of the Ni, Fe and Co-based alloys have similar densities, this method of presentation has little effect on their relative strength merits. (Nimonic 100 is of slightly lower density than Nimonic 95 and Nimonic 90 and so the improvement in performance is somewhat greater than that apparent from the laboratory data presented in Table VI). On this basis, the resistance to centrifugal stresses of stress-relieved molybdenum at 982°C is superior to that of the tantalum-containing cobalt-based alloys. At this temperature, the stress-relieved molybdenum alloys are still considerably superior in strength to any other metallic alloy.

Comparative creep data for wrought and cast alloys are given in Table VIII. The notable feature of this data is that the stress to produce 0.1 per cent or 0.5 per cent creep in 100 or 300 hours for cast cobalt-based alloys is considerably lower than that for wrought Ni-based alloys, although the 100 hour and 300 hour rupture strengths are similar. This data serves to show that comparison of stress-to-rupture data only as an evaluation of performance can be misleading.

The small amount of available comparative fatigue data is confined to British alloys (see Table IX). Comparable fatigue strength/rupture strength ratios are given in Table X. The ratios for Nimonic 90 and 95 are higher than for the iron and cobalt-based alloys. The only casting alloy represented in G.34, and the ratio is lower than its wrought counterpart G.32 or any of the other wrought alloys except G.40. No fatigue data has yet been published for Nimonic 100.

Comparable oxidation test data for the alloys considered is not available. Alloys containing 20 per cent or more chromium possess adequate oxidation resistance up to 1100°C. A few of the alloys contain only 10/15 per cent chromium but they also contain sufficient aluminium to promote adequate resistance to oxidation. Coatings, 0.005/0.010 in. in thickness, have been devised[20] for molybdenum such that protection against

*The term "specific rupture strength" is used here to indicate the laboratory rupture strength divided by the ratio of the density of the material to the density of Nimonic 90.

oxidation is possible for at least 500 hours in circulating air at 982°C.   A chromium/silicon/aluminium coating[20], deposited by metal spraying techniques, has some capacity to withstand thermal shock without damaging its protective ability.

Very little data is available on the relative thermal shock resistances of the metals and alloys considered.   A number of British firms, particularly the suppliers of steels and creep resistant alloys, have devised laboratory thermal shock tests for assessing the merits of their products for nozzle guide vane applications.   Only a few rotor blade materials have been tested.   Their relative performances varied with the nature of the test conditions and the geometry of the specimen. The performances of cast cobalt-based alloys e.g. G.34 and X40, as assessed by the number of cycles to produce cracking on heating and cooling, were found to be both superior and inferior to Nimonic 80 and Nimonic 90 according to the nature of the test and the temperature range of the cycle.

3.0   Ceramics and cermets

3.1   Historical development

The usefulness of ceramics for gas turbine blading was first investigated[26,27] in Germany during the last war, the stimulus being the shortage of critical elements such as nickel for alloy blading. The low densities, inherent oxidation resistance and high short time breaking strengths of the pure oxides were obviously attractive. Although blades were manufactured, very little engine testing was carried out.   From this and subsequent work in the United States, it became apparent that the pure oxides, with the exception of fused silica, had inadequate thermal shock resistance.   Fused silica was considered to have inadequate strength-at-temperature advantage over metallic alloys.   Beryllia was considered to possess superior thermal shock resistance to alumina, zirconia and thoria, and this led the Bureau of Standards to develop beryllia-containing porcelains.   The N.A.C.A. carried out[28] short time tensile strength, creep and stress-to-rupture tests up to 1150°C on a number of these porcelains, the best being a composition designated 4811C.   Blades in this material and in sillimanite (a beryllia-free porcelain) were tested[29] in experimental engines.   Failures of the sillimanite blades occurred in the root fixings due to stress concentrations.   The 4811C blades were tested for 50 hours at 980°C and speeds up to 14,000 rev/min., at the end of which failure by thermal shock of all the blades occurred due to failure of the air supply.   It was concluded that oxide-based ceramics were unsuitable for gas turbine blading.

During their investigations into pure oxides, German research workers had realised that the brittleness of oxide ceramics such as alumina might be reduced by addition of metals without sacrificing their high temperature strength and oxidation resistance.   Although iron/alumina compositions were unsatisfactory, this work stimulated American and later British research workers to study the wetting of alumina by metals and finally to concentrate on the chromium/alumina system.   Blackburn and Shevlin (Ohio State University) found[30] that the thermal shock resistance of 30 per cent $Cr-Al_2O_3$ was poor, and that (as is generally the case) this property improved and the rupture strength diminished with increasing metal content.   The properties of 30 per cent Cr- 72 per cent Cr- and recently 52 per cent Cr/13 per cent Mo alumina bodies have been evaluated[30,31,32].

Plessey Co. Ltd. have carried out[33] under M.O.S. contract researches on
the development of Cr-Al2O3 compositions (mainly 20 per cent and 40 per
cent Cr) during the last five years.   The Haynes Stellite Division of the
Union Carbide and Carbon Corporation, U.S.A., supply[34] commercially a
79 per cent Cr-Al2O3.   A similar composition (about 75 per cent Cr-Al2O3)
is also supplied by Morgan Crucible Co., London.   Some effort has been
devoted to assessing the usefulness of other oxide ceramics for cermets.
The strength-at-temperature properties of nickel/magnesia cermets have
proved to be unattractive.

        Considerably greater attention has been devoted to assessing the
usefulness of ceramic-type compounds such as carbides, nitrides, borides
and silicides formed by the combination of relatively small non-metal atoms
e.g. carbon, nitrogen, boron and silicon with metals, particularly the
transition metals (Group IV to VI of the Periodic Table).   The transition
elements so far considered for combination with these non-metals are, in
order of increasing atomic weight, titanium, vanadium, chromium, zirconium,
niobium, molybdenum, hafnium, tantalum and tungsten.

        These compounds are characterised by thermal and electrical conduc-
tivities of the same order of magnitude as pure metals, by high hardness
values, melting points and moduli of elasticity, and by their chemical
stability, at least at room temperature.   The major development efforts
have been concentrated on the carbides, particularly on metal-bonded
carbides.

        Since World War II, considerable efforts have been made, mainly
by cutting tool manufacturers, to develop metal-bonded carbides for gas
turbine blading, but it was over 30 years ago that cutting tools having
a tool tip or cutting edge consisting of cobalt-bonded tungsten carbide
were developed.   The superior performance of these tools over high speed
tool steels was to a large extent due to their high resistance to defor-
mation at the temperatures incurred in high speed cutting operations.
It was also found[35] that additions of titanium carbide to the cobalt-
bonded tungsten carbide considerably improved machining performance due
to enhanced oxidation resistance.   Titanium carbide (specific gravity
4.9) is considerably less dense than tungsten carbide (specific gravity
15.8), more oxidation resistant than either tungsten carbide or zirconium
carbide (specific gravity 6.44) and possesses good thermal shock resistance.
The attractively low density coupled with high strength, high thermal con-
ductivity, low expansion and general structural stability, were the main
incentives for extensive research work on 'cemented' or metal-bonded
titanium carbide.   Good bonding was obtained with nickel, cobalt, chromium,
tungsten or molybdenum.   While high temperature strengths comparable or
superior to the "superalloys" (i.e. X40 type) were obtainable, the best
oxidation resistance (on the 80 per cent TiC 20 per cent Co) was inadequate.
Two approaches were adopted viz. modification of the composition of the
carbide matrix, and modification of the binder composition.   Additions
of a solid solution of niobium, tantalum and titanium carbides were found[36]
to be markedly effective.   Kennametal Inc. added 15 per cent of this solid
solution (NbC/TaC/TiC) to their K138 composition (80 per cent TiC, 20
per cent Co) and marketed K138A (65 per cent TiC, 15 per cent solid
solution, 20 per cent Co); subsequently this and other improved com-
positions became commercially available.   A similar improvement in oxi-
dation resistance was obtained by using a solid solution of chromium
carbide (Cr2C3) in titanium carbide.   This approach was adopted[37] by
Hard Metal Tools Ltd., Coventry, their preferred composition (40N) being
54 per cent TiC, 6 per cent Cr2C3 and 40 per cent nickel.   While the
results obtained using pure chromium as a binder have not been outstanding,

Co-Cr, Ni-Cr and Co-Ni-Cr alloys have been successfully used[38,39], e.g.
in the 'WZ' series of bonded carbides commercially supplied by
Metallwerk Plansée, Austria and in the 'Elmet IR' compositions (similar
to the 'WZ' series) manufactured by Metro-Cutanit Ltd., Warrington,
Lancs.   Whether chromium is added as chromium metal to the binder or as
chromium carbide to the matrix, it is usual for it to be present in
both the binder (as chromium in solid solution) and the matrix (as
chromium carbide in solid solution).   A third method of improving
oxidation resistance viz. by means of protective coatings has not been
utilised commercially, although satisfactory coatings (e.g. high
chromium content glazes) have been obtained.

         All the above types of metal-bonded carbide can be produced
by cold pressing or extrusion, followed by sintering, or by hot pressing
(unless the binder content is too high).   A departure from this method
of manufacture is that employed[40] by Sintercast Corporation.   A porous
skeleton of sintered titanium carbide (or a TiC-based solid solution of
carbides) is infiltrated with a molten creep resistant alloy.

         Few carbides other than titanium carbide have been seriously
considered as a base for high strength cermets.   A series of cemented
chromium carbides possessing high oxidation resistance have been deve-
loped[41] by the General Electric Co. (U.S.A.) but high temperature
strength is not claimed.   At least three carbides formed by union of
carbon with elements other than the transition metals have been inves-
tigated viz. the carbides of boron, silicon and beryllium.   Hot pressed
boron carbide is commercially supplied for such components as sand-
blasting nozzles but its thermal shock resistance is poor.   Cermets
containing titanium carbide and boron carbide (giving titanium diboride
in the structure) possess[42] excellent oxidation resistance at 1100°C,
and a 100 hour rupture strength greater than 25,000 p.s.i. at 982°C.
Hot pressed beryllium carbide has been found to possess relatively low
bend strength (13,000 p.s.i.) at room temperature.   Silicon carbide
has received attention for high strength-at-temperature applications
only in recent years.   Silicon carbide is usually bonded with clay and
is of low strength, but bonding with silicon[43] and silicon nitride (SiN)
respectively has produced much stronger bodies.   Carborundum Co.,
Manchester supply[44] 'Niafrax' silicon carbide (bonded with SiN).
Morgan Crucible Co. have developed[45] and installed pilot plant for the
manufacture of a silicon carbide body supplied under the trade name
'I.C. Silicon Carbide'.   Research work on suitable methods of bonding
silicon carbides, and evaluation of properties are being carried out
by the British Ceramic Research Association under M.O.S. contract.

         The compounds formed by the transition metals and nitrogen,
boron and silicon have only recently been studied, mainly because
of the concentration of technical interest on carbides.   Silicides,
borides and metal-bonded borides are manufactured[46] by the American
Electro-Metals Corporation, U.S.A. and a subsidiary, the Borolite
Corporation, attention being so far centred on molybdenum disilicide
and bonded zirconium and chromium borides.   The N.A.C.A. have
evaluated[47,48,49] the properties of a number of these materials.
The Plessey Company Limited are investigating[50] intermetallic com-
pounds under M.O.S. contract, their research effort being concentrated
on silicides.   Silicon nitride is being studied by the British Ceramic
Research Association.   More recently, intermetallic compounds such as
aluminides (e.g. nickel aluminide, NiAl) and titanides (e.g. chromium
titanide, Cr_2Ti) have been investigated.

3.2   Evaluated properties

Reported data on ceramics and cermets of possible usefulness for gas turbine blading are given in Tables XI to XXIII.   For any one material, it is rare to find that a reasonably comprehensive evaluation of all relevant properties has been made.   Preliminary tests on experimental compositions are usually confined to bulk density or porosity measurements, oxidation tests and bend strength determinations.   The oxidation test results are usually based on weight gain or loss measurements, and not on degree of penetration or loss of strength which permits useful comparison of relative oxidation resistances.   Bend strength rather than tensile strength measurements are made because both the preparation of the specimens and the testing techniques are much simpler. (In tensile testing brittle materials it is difficult to provide truly axial loading without incurring bending stresses.)   However, bend strength results for different materials are not generally comparable because different investigators use different test conditions, e.g. 3-point or 4-point loading, different distances between loading points, varying shape and size of cross-section of specimen, etc.   Very little bend creep or tensile creep data has been published.   The usual means of assessing high temperature strength is the stress to rupture test.   In many cases it is necessary to assume that true axial loading is maintained during the tests as no effort is made to describe the test conditions.   This test also gives some indirect information on the oxidation resistance of the material after 10, 100 or 300 hours testing.   For some materials (e.g. metal-bonded carbides) rupture tested at $1093°C$, it is dangerous to extrapolate data to longer rupture times because oxidation may so diminish the cross-sectional area that the slope of the stress/log. time curve may increase rapidly.

The chemical compositions of two beryllia porcelains, sillimanite and metal-bonded carbides are given in Table XI.   The nominal compositions of the metal/oxide bodies are given in their designations;   the compositions of the commercial silicon carbides and the borides have not been published.   Details of the source and method of manufacture are given in Table XII.   In all cases no heat treatment has been given after the sintering or hot pressing operations.

Density, thermal expansion and thermal conductivity data are given in Table XIII.   The very low values of thermal expansion of fused silica and graphite explain their reputedly high resistance to thermal shock. The thermal conductivities of the metal-bonded carbides are appreciably greater than that of 30 per cent $Cr-Al_2O_3$ and lower than that of 79 per cent $Cr-Al_2O_3$.

Data on tensile strength and Young's Moduli are given in Table XIV. The tensile strengths of the oxides are all low in comparison with heat resistant alloys.   The Young's Moduli values for alumina, the low chromium-alumina, the carbides and metal bonded carbides are at least 50 per cent greater than that of the creep resistant metallic alloys.   Both fused silica and graphite possess low tensile strengths;   the value for graphite is so low that even if suitably protected against oxidation, it is unlikely to be applicable in rotor blading.

Stress-to-rupture data for ceramics and cermets are given in Table XV, and in Figures 6 and 7.   Comparative stress/temperature curves for 100 hour rupture life, with Nimonic 100 for comparison, are given in Figures 8 and 9.   The metal/oxide cermets have somewhat greater strength than the metal-bonded carbides at $982°C$ and maintain their strength above

982°C to a greater extent.   Specific 100-hour rupture strength data
relative to Nimonic 90 are given in Table XVI, and Figures 10 and 11.
On this basis the best bonded borides have superior rupture strengths
to the best bonded carbides at 982°C;   the latter have similar strengths
to molybdenum disilicide.   At the same temperature, the metal/oxide
cermets and the bonded borides have comparable rupture strengths.   The
beryllia-containing porcelains have superior specific rupture strengths
to any of the other ceramics and cermets.

        In the absence of comparative tensile creep data, the relative
bend creep performances of several ceramics and cermets are indicated[65]
in Table XVII.   The most creep resistant compositions are obviously
the 20 per cent chromium-alumina, and the commercial silicon carbide.
At 1,000°C, the high chromium-aluminas are superior to the metal-bonded
carbides.   The least creep resistant material at 1,000°C is Nimonic 95,
fused silica being comparable.

        The oxidation test data in Table XVIII shows the excellent
resistance of the 30 per cent Cr-Al_2O_3 and molybdenum disilicide at
1,200°C, and that of the bonded borides at 1,100°C.   Although the
weight gain figures for Nimonic 80A (tested under similar conditions
to WZ 12C) are somewhat higher than those obtained elsewhere, the
metal-bonded carbides containing a solid solution of titanium, niobium
and tantalum carbides appear to possess comparable oxidation resistance
up to 1,100°C.   Oxidation test data are not available for graphite but
it is generally accepted that oxidation is rapid above 450/500°C.
Development of protective coatings based on glazes, silicides or silicon
carbide is being pursued by various investigators.

        Very little laboratory fatigue test data, even at room temperature,
have been published, and no comparative data is available.   The fatigue
strength (Wohler) at 49×10^6 cycles of the metal-bonded carbide 4UN at
750°C is $\pm$ 30,200 p.s.i. (compare $\pm$ 39,400 p.s.i. for Nimonic 90 at
750°C after 45×10^6 cycles).

        The thermal shock resistance of ceramics and cermets has always
been considered their Achilles heel.   The relative performance of per-
fectly elastic, i.e. perfectly brittle, materials can be roughly pre-
dicted from the relative values of the index $\dfrac{k\sigma}{E\alpha}$ where k is the

thermal conductivity, σ the tensile strength, E Young's Modulus and α
the coefficient of expansion, assuming that the size and shape of the
specimen and the conditions of heat transfer are identical.   Unfortu-
nately, data for each of these four properties at the temperature at
which the maximum thermal stress occurs (about 80 per cent of the
temperature from which cooling occurs) is usually not available.   In
ductile materials e.g. metals or alloys, the capacity for relieving
the stress by deformation is probably more important than its physical
and mechanical properties, and hence the above index is inapplicable
to such materials.   In cermets, even the relatively low ductility
at elevated temperatures is likely to enhance thermal shock resistance,
and so a low performance index relative to a ceramic may not be a
criterion of service behaviour.   Thermal shock indices for ceramics
and cermets are given in Table XIX.   The carbides, metal-bonded car-
bides and fused silica have a high thermal shock rating on this basis.
Alumina is rather over-rated.

Experimental measurement of thermal shock resistance is often crude, the precise experimental conditions are rarely described and the results are seldom useful for comparison with others.   The N.A.C.A. thermal shock test is satisfactory, although the testing procedure could be improved. In this test, disc specimens 2 in. diameter and $\frac{1}{4}$ in. thick are heated in a furnace and cooled in a constant velocity air stream.   Evaluation is based on the ability of the ceramic or cermet to withstand without fracture or cracking 25 cycles of quenching from each of four tempera- tures.   If failure occurs in less than 25 cycles at one temperature, further testing at the next highest temperature is not pursued.   The results are given in Table XX.   It is evident that the metal-bonded carbides are superior to the other ceramics and cermets, although the bonded Cr borides and nickel aluminide have not been tested using the higher cooling air velocity.   It is seen in Table XXI that the order of merit of performance determined from the thermal shock indices is con- firmed by experiment.   However the important consideration is the cor- relation of the calculated and laboratory performance data with the behaviour of the materials tested in the form of gas turbine blading under actual or simulated engine conditions.   Unfortunately, although the results of several hot spinning and engine tests have been reported, these tests were not designed to evaluate thermal shock performance only. Failure could be clearly attributed to thermal shock in only a few cases e.g. the 4811C blades[28].   Fatigue failures in the roots (caused by resonant vibrations), "fragmentation" failures due to impact, and disc failures due to overheating of the rim (in the case of metal-bonded carbides which possess higher thermal conductivities than alloy blades) predominate.   It would appear, however, that many of the metal-bonded carbides have adequate thermal shock resistance for aircraft gas turbines, but the shape and size of the blades, particularly the thickness of the leading and trailing edges, will obviously influence this property.   The N.A.C.A. consider that 72 per cent $Cr-Al_2O_3$ has barely sufficient thermal shock resistance for blading and from this it could be inferred that only those materials with a superior N.A.C.A. laboratory test performance merit consideration.   The 52 per cent $Cr/13$ per cent Mo/Al_2O_3 compositions (designed so that the metallic alloy and ceramic phases have near-identical thermal expansions) is considered[32] to have excellent and consistent thermal shock resistance when tested in the form of solid nozzle diaphragm blades.   The test results are an appreciable improvement over those obtained for 72 per cent $Cr-Al_2O_3$ tested under the same conditions, and are similar to those obtained for the metal-bonded carbide, FS27.

The major deterrent to the application of ceramics and cermets in gas turbine blading has not yet been directly considered viz. lack of ductility.   As previously pointed out, the presence of ductility enhances thermal shock resistance.   The absence of ductility means that in root fixing design, it is imperative that stress concentrations are minimised by avoiding large or sudden changes in section and by using generous radii. The absence of ductility means that virtually the same handling precautions must be taken as in the pottery industry.   Assuming that the design problems can be overcome (tests on experimental root fixings have given promising results), and assuming that extreme care in handling coupled with frequent inspections for damage is simply a matter of "educating" the user, there remains the problem of accidental damage during engine operation.   Under rapid rates of loading, cermets can be considered to be equally as brittle as ceramics.   If extraneous 'foreignbodies' such as nuts, bolts, parts of the combustion chamber, etc. should pass through the turbine, it is probable that portions of one or more blades will break away, and prior to their passage out of the engine catastrophic

damage to the remaining blades may occur.   Such damage can only be
prevented if it can be guaranteed that such accidents will not occur.
Also, it is necessary to guarantee a minimum level of performance for
the blading.   Failure of one blade by creep, fatigue or thermal
shock could lead to complete damage of the remainder by impact.   Such
total damage has occurred in experimental engines.

        The impact strengths of some ceramics and cermets have been
evaluated, usually by measuring the energy required to fracture speci-
mens located in a stationary anvil and struck by a weight moving at a
velocity of about 10 ft/s.   The weight may be attached to a pendulum
as in the Charpy, Riehle, Baldwin and Hounsfield machines, or dropped
from a height sufficient to fracture the specimen (N.A.C.A. test).
The results of room temperature impact tests are given in Table XXII.
Being essentially brittle materials, notching (unless it is very
severe) has little effect on the impact strength and most tests are
carried out on unnotched specimens.   Only the results obtained on any
one machine are comparative.   The blade alloy, X40, has 15 to 30 times
the impact strength of the cermets.   The impact strength of the inter-
metallic compound, nickel aluminide, is superior to the metal-bonded
carbides.   The improvement in the impact resistance of cermets with
increasing binder content is not as marked as the decline in rupture
strength.   The chromium/alumina cermets are much less resistant to
impact than the metal-bonded carbides, while 'Niafrax' silicon carbide
and Zr Boride 101 are very weak in this respect.   At elevated tempera-
tures some improvement in impact strength may be expected but the
published data (see Table XXIII) are not encouraging.   Endeavours to
improve impact strength properties are being made, e.g. by spheroidisa-
tion of the carbides in metal-bonded carbides and by producing a metal-
rich surface layer by infiltration.   Obviously a compromise must be made
between adequate rupture strength and impact strength.   Materials that
are strong at elevated temperatures are resistant to deformation.   For
resistance to impact or fragmentation, plastic deformation is necessary.
According to Glaser[68], an impact strength of 20 ft. lb. (Charpy test) is
the immediate target (compare 4 ft. lb. for titanium carbide bonded with
50 per cent of a nickel/chromium/cobalt alloy).

4.0   Comparison of the properties of metals, alloys, ceramics and
         cermets

        The primary requirement for gas turbine rotor blading, viz. an
adequate level of strength maintained at the operating temperature for
the specified engine life, will be first considered.   Comparative 100
hour rupture stress data for representative metals, alloys, ceramics
and cermets at 871°C and 982°C are given in Figures 10 and 11.   On a
relative density basis, i.e. relative to Nimonic 90, the 100 hour
rupture stress data are shown in Figures 12 and 13.   At 871°C, (Figure
12) and even more markedly at 982°C (Figure 13) the superiority of the
ceramics and cermets over the nickel, cobalt and iron-based alloys is
clearly evident.   At 982°C, the metal-bonded carbides have lost
approximately 50 per cent of their rupture strength at 871°C.   The
bonded borides and chromium/alumina compositions are obviously
superior to the bonded carbides.   Even on a relative density basis
the wrought molybdenum alloys are still highly attractive and it is
hoped that adequate protection of blading against oxidation under
operating conditions can be achieved.   Of the ceramics and cermets,
molybdenum disilicide, 4811C, Zr boride 101, 30 per cent Cr-Al2O3

and probably 72 per cent $Cr-Al_2O_3$ have inadequate thermal shock resistance
for gas turbine blading.   Assuming that the brittle characteristics of
the remaining cermets (viz. the metal-bonded carbides, e.g., WZ1, K161B
and TC-66-I, the Cr boride 301 and the 52 per cent Cr/13 per cent Mo/Al_2O_3
composition) are not objectionable then they are potentially useful for
gas turbine rotor blading.   The 100 hour rupture stress/temperature
curves for these cermets are included in Figure 14.

The respective temperatures at which a 100 hour rupture life can
be obtained for Nimonic 90 under centrifugal stresses of 8, 10, 11 and
13.4 tons/sq. in. were derived from the stress/temperature curve for
Nimonic 90 (Figure 3).   For the same centrifugal loading the centrifugal
stresses for representative alloys and cermets were calculated and the
corresponding temperatures for the same rupture life were derived from
their stress/temperature curves.   The results are given in Table XXIV.
In this way the temperature advantage over Nimonic 90 that can be obtained
with the potentially useful cermets and metallic materials is apparent.
Nimonic 100 has a 30/40°C advantage over Nimonic 90.   The strongest
Co-based casting alloy, 73J, is competitive with Nimonic 100.   The
strongest metal-bonded carbides, K161B and TC-66-I have 80/90°C tempera-
ture advantage over Nimonic 100 and the 52 per cent Cr/13 per cent Mo/
Al_2O_3 has 120/130°C advantage.   Pure stress-relieved molybdenum has an
appreciable temperature advantage over Nimonic 100 only at the lowest
value of 100 hour rupture stress.   The 0.45 per cent Ti - Mo alloy
shows a temperature advantage of approximately 180°C over Nimonic 100
and this value is maintained for the rupture stress range considered.
It is probable that recrystallised or silicon-bonded silicon carbides
will be developed with comparable specific strength to the bonded borides
and possibly greater thermal shock resistance.

Assuming that nickel-, cobalt- or iron-based alloys of superior
strength to Nimonic 100 are ultimately developed, it is unlikely that
they will retain their strength at temperatures as high as that possible
for the above-mentioned cermets, or for molybdenum alloys.   Nevertheless,
the brittle characteristics of the cermets and the poor oxidation resis-
tance of molybdenum alloys have prevented their application and the
replacement of current metallic alloys.   Even if adequate mechanical
shock resistance is obtainable in cermets, there are other problems to
which not very much thought has been given.   For example, it is
essential that a minimum level of strength can be guaranteed for the
blades which, in the case of cermets, would be individually made either
by hot pressing or sintering.   As for blade castings, conventional
non-destructive inspection techniques such as X-ray examination are only
useful for revealing gross defects.   It may therefore be necessary to
use inspection methods such as cold or hot spin tests to guarantee both
soundness and a minimum level of strength.   The problem of obtaining
uniformity of production, e.g. reproducibility of size and shape as well
as properties has not received serious attention.   The finish machining
of thin trailing edges by diamond grinding is far from desirable in
quantity production.   It is possible that the designer will have to
depart from traditional practice and employ not only different root
fixings but thicker leading and trailing edges for ease of production.
If, in the case of molybdenum alloys the oxidation resistance problem
is solved, engineers may not accept protective coatings which are likely
to have the same brittle characteristics as ceramics and cermets.   The
problem of obtaining uniformity of composition and keeping detrimental
impurities to a minimum level is being investigated, the latter being
important if room temperature brittleness is to be avoided.   Further

work on chromium-based alloys is necessary to determine whether brittle-
ness either of the manufactured alloy or developed on heating in air at
elevated temperatures can be prevented.   It is not known whether any
research work is being carried out on niobium alloys but it is obvious
that if alloying additions can be made to improve simultaneously creep
strength and oxidation resistance without resorting to the use of
protective coatings, such alloys are the most likely successors to the
nickel-based alloys.

5.0   Conclusions

(1)   A review and analysis of available data on metals, alloys,
ceramics and ceramic/metal composites (cermets) in use or potentially
useful for aircraft gas turbine blading have been made.

(2)   From the data, it is evident that the best wrought
nickel-based alloy, Nimonic 100, is unlikely to be useful at blade
temperatures above approximately 880°C assuming a centrifugal stress of
8 tons/sq.in. and a 100 hour rupture life.   Under the same centrifugal
loading, Nimonic 100 has a 30/40°C temperature advantage over Nimonic 90.

(3)   No cobalt- or iron-based alloy, whether wrought or cast, is
superior under the above conditions to Nimonic 100.   The strengths of
wrought nickel- and cobalt-based alloys fall off more rapidly with
temperature above 880°C than cast nickel- or cobalt-based alloys or some
wrought iron-based alloys.

(4)   There are no other blade materials immediately available
which can replace Nimonic 90 (and eventually Nimonic 100) for higher
temperature service.   Metallic alloys (based on chromium and molybdenum
respectively) and cermets (predominantly metal/carbide, metal/oxide and
bonded boride compositions) possessing similar or superior strength at
appreciably higher temperatures have been developed but their inadequacy
in other respects precludes their application.

(5)   The attractive high temperature strength properties of
molybdenum and its alloys cannot be utilised until reliable coatings
for complete protection against oxidation are developed and accepted.

(6)   The high temperature strength properties of niobium
indicate that if and when suitably alloyed to improve its oxidation
resistance, it may prove more attractive as a base metal than molyb-
denum or chromium.

(7)   Chromium-based alloys having superior stress-to-rupture
properties to Nimonic 100 have been developed but their brittleness
prevents their application.   It is possible that ductile alloys may
be manufactured by careful processing to eliminate detrimental
impurities.

(8)   The pure ceramics, i.e. oxides, carbides, borides,
nitrides and silicides so far developed are not considered useful for
turbine blading because of inadequate thermal shock resistance,
inadequate strength or extreme brittleness.

(9)   Bonded carbides and borides and metal/oxide cermets
possessing good thermal shock resistance and similar or superior strength
to Nimonic 100 at appreciably high temperatures have been developed.
Their poor mechanical shock resistance has precluded their application
in production engines.

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TABLE I

Properties of pure annealed metals

Metal	Melting Point [*] °C	[**] Density gms/c.c.	Stress for 1% Compressive Creep in 24 hours at 1000°C × 10⁻³ p.s.i. [**]	Stress/Density at 1000°C	Metal
Titanium	1820	4.5	0.22	0.049	Titanium
Zirconium	1750	6.5	0.22	0.033	Zirconium
Vanadium	1735	6.1	0.67	0.112	Vanadium
Niobium	2415	8.4	5.24	0.74	Niobium
Tantalum	2996	16.6	6.7/8.9	0.40/0.53	Tantalum
Chromium	1890	7.1	4.5/6.7	0.625/0.94	Chromium
Molybdenum	2625	10.4	6.7/8.9	0.65/0.85	Molybdenum
Tungsten	3410	19.3	13.4	0.69	Tungsten
Platinum	1773	21.4	0.22	0.012	Platinum
Palladium	1554	11.9	0.67	0.067	Palladium
Rhodium	1966	12.4	6.7	0.535	Rhodium
Iridium	2454	22.4	13.4	0.60	Iridium
Iron	1539	7.87	1.07	0.134	Iron
Cobalt	1495	8.9	1.38	0.158	Cobalt
Nickel	1455	8.9	0.55	0.067	Nickel

[*] Reference 2
[**] Reference 3

TABLE II

Chemical compositions of metallic alloys

Material Designation	Nominal chemical composition, % by weight													Ref.
	C	Mn	Si	Cr	Ni	Co	Mo	W	Nb	Ti	Al	Fe	Others	
Wrought Ni-based alloys:														
Nimonic 90	0.1 max	1.0 max	1.5 max	18/21	bal.	15/21	–	–	–	1.8/3.0	0.8/2.0	5.0 max	–	9
Inconel X 550	0.03	0.5	0.3	15	73	–	–	–	0.6	2.5	1.1	6.5	–	10
Nimonic 95	0.15 max	1.0 max	1.0 max	18/21	bal.	18/21	–	–	–	2.3/3.5	–	5.0 max	–	9
Inco 739	0.07	0.05	0.2	15	77	–	–	–	–	1.7	2.7	1.0	–	10
Waspaloy	0.10	1.0	0.75	19.5	55	13.5	4.25	–	–	2.5	1.25	2.0	–	10
M252	0.15	1.0	0.65	19	51	10	10	–	–	2.5	0.87	5.0	–	10
Nimonic 100 ‡	0.22	0.03	0.24	9.9	57.4	21.0	5.85	–	–	1.67	3.8	0.23	–	–
Inco 700	0.10	0.05	0.2	15	49	28	3	–	–	2	3	0.5	–	10
Cast Ni-based alloys:														
GUY	–	–	–	12/15	71/65	–	5/6	–	2	–	5.5/7.0	4.5	–	11
95M-255	–	–	–	–	66.5	–	25.5	–	–	–	7.0	1.0	–	11
GMR.235	0.15	0.25 max	0.6	15.5	bal.	–	5.55	–	–	2.0	3.0	10.0	0.05B	12
Wrought Fe-based alloys:														
G42B ✕	–	–	–	19	15	25	–	–	–	–	–	rem.	–	13
G40 ✕	0.2	–	–	20	25	–	–	–	–	–	–	rem.	–	14

‡ N.G.T.E. Analysis

✕ Basic composition

TABLE II (Cont'd)

Nominal chemical composition, % by weight

Material Designation	C	Mn	Si	Cr	Ni	Co	Mo	W	Cb	Ti	Al	Fe	Others	Ref.
Wrought Co-based alloys:														
G32	0.3	-	-	19	12	45	2	-	1.2	-	-	17	2.8V	15
S816	0.38	1.2	0.4	20	20	43	4	4	4	-	-	4	-	10
Cast Co-based alloys:														
G34	0.8	-	-	20	12	45	2	-	1.2	-	-	16	2.8V	16
422-19	0.4	0.6	0.6	24	17	51	6	-	-	-	-	1.0	-	10
X40	0.4	0.6	0.6	25	10	55	-	8	-	-	-	1.0	-	10
H.S.36	0.4	1.2	0.5	19	10	54	6	14.5	-	-	-	1.0	-	10
73J	0.75	1.0	-	23	6	60	6	-	-	-	-	-	2 Ta	17
111VT2-2	1.11	-	-	23	-	68	3	-	-	-	-	-	2 Ta	18
100NT2	1.0	1.5	-	20	30	20	-	2.2	-	-	-	17	2 Ta	18
Sintered Vitallium	nil	-	-	30	-	64	-	6	-	-	-	-	-	19

TABLE III

Supplier, method of manufacture and heat treatment of metals and alloys

Material Designation	Supplier	Method of Manufacture	Heat Treatment	Ref.
Nimonic 90	Henry Wiggin & Co., Ltd., Birmingham	Forged	Solution treated, aged at 900°C	9
Inconel X 550	International Nickel Co.	Forged	Not given	10
Nimonic 95	Henry Wiggin & Co., Ltd., Birmingham	Forged	Solution treated, aged at 700°C	9
Inco 739	International Nickel Co.	Forged	Not given	10
Waspaloy	"	Forged	Not given	10
M 252	"	Forged	Not given	10
Nimonic 100	Henry Wiggin & Co., Ltd., Birmingham	Forged	Solution treated and aged	9
Inco 700	International Nickel Co.	Forged	Not given	10
GUY	Experimental only	Cast	None	11
95M-255		Cast	None	11
GMR 235	General Motors, U.S.A.	Cast	Not given	12
G 42 B	Wm. Jessop & Sons, Sheffield	Forged	Not given	13
G 40		Forged	Not given	14
G 32	Wm. Jessop & Sons, Sheffield	Forged	Solution treated, oil quenched, aged at 750°C	15

TABLE III (Cont'd)

Material Designation	Supplier	Method of Manufacture	Heat Treatment	Ref.
S 816	Allegheny Ludlum Co., U.S.A.	Forged	Solution treated, aged at test temperature	10
G 34	Wm. Jessop & Sons, Sheffield	Cast	None	16
422-19	Haynes Stellite Co., U.S.A.	Cast	Aged 730°C	10
X 40	Deloro Stellite Co., Birmingham	Cast	Aged 730°C	10
H.S. 36		Cast	Aged 730°C	10
73 J		Cast	Aged 730°C	17
111 VT2-2	Experimental only	Cast	None	18
100 NT 2		Cast	Solution treated, water-quenched	18
Sintered Vitallium	Experimental only	Pressed and sintered	None	19
60 Cr-15 Fe-25 Mo		Cast	None	4
60 Cr-25 Fe-15 Mo	Experimental only	Cast	None	4
Mo and alloys	Climax Molybdenum Co.	Arc-cast and swaged	Stress-relieved or recrystallised	20
Niobium	Experimental only	Arc-cast and swaged	Annealed	21

TABLE IV

Physical properties of metals and alloys

Material Designation	Density gms/c.c.	Mean Thermal Expansion in/in/°C. x 10^6 at			Thermal Conductivity (c.g.s.) at				Ref.
		20/100°C	20/800°C	20/900°C	100°C	600°C	800°C	900°C	
Wrought Ni-based alloys:									
Nimonic 90	8.27	11.6	16.0	17.0	0.030	–	–	0.069	9
Nimonic 95	8.11	12.8	16.0	17.0	–	–	–	–	9
Nimonic 100	8.04	12.4	15.7	16.8	–	–	–	–	9
Cast Ni-based alloy:									
GUT	8.35	–	–	–	–	–	–	–	11
95 M-255	8.0	–	–	–	–	–	–	–	11
GMR 235	8.45†	–	–	–	–	–	–	–	12
Wrought Fe-based alloys:									
G 42 B	8.23	15.0	17.0	17.2	0.030	–	(0.062)	(0.065)	13
G 40	8.02	15.2	17.3	17.6	–	–	–	–	14
Wrought Co-based alloys:									
G 32	8.26	14.8	17.5	18.0	0.035	–	0.062	–	15
S 816	8.59	–	17.6	17.9	–	–	–	–	22
Cast Co-based alloys:									
G 34	8.19	12.2	15.6	16.2	0.035	–	0.062	–	16
422-19	8.31	–	15.5	–	(0.031)	0.048	–	–	23
X 40	8.61	–	16.54	16.6	(0.033)	0.052	–	–	23
H.S.36	10.25†	–	–	–	–	–	–	–	23
73 J	8.47†	–	–	–	–	–	–	–	17
111 VT2-2	8.56†	–	16.15	16.25	–	–	–	–	18
100 WT2	8.37†	–	16.15	16.25	–	–	–	–	18
Sintered Vitallium	8.44	–	16.3	–	–	–	0.059	–	19

( ) - extrapolated   † Density calculated from chemical composition

TABLE IV (cont'd)

Material Designation	Density gms/c.c.	Mean Thermal Expansion in/in°C. x 10⁶ at			Thermal Conductivity (c.g.s.) at				Ref.
		20/100°C.	20/800°C.	20/900°C.	100°C.	600°C.	800°C.	900°C.	
Cast Cr–based alloys:									
60 Cr/15Fe/25 Mo	7.87	–	8.60	–	–	–	–	–	4
60 Cr/25Fe/15 Mo	7.63	–	8.20	–	–	–	–	–	4
Molybdenum	10.22	4.82	5.7	–	0.31	0.29	0.275	0.25**	20
Tantalum	16.6	6.5	6.6	–	0.129	–	–	–	2
Tungsten	19.3	4.5	4.6	4.6ˣˣ	0.38	0.29*	–	0.25**	2
Chromium	7.1	6.5	8.5	–	0.16	–	–	–	2
Niobium	8.6	7.2	–	–	–	–	–	–	2

* 500°C

** 1000°C

xx 20/1000°C

TABLE V

Data on tensile strength and Young's Modulus for metals and alloys

Material Designation	Tensile strength, x 10^{-3} p.s.i. at					Young's Modulus x 10^{-6} p.s.i. at					Ref.
	20°C	800°C	816°C	871°C	900°C	20°C	800°C	816°C	871°C	900°C	
Wrought Ni-based alloys:											
Nimonic 90	166.0	85.0	76.0	–	–	28.0	20.0	20.0	–	19.0	9
Nimonic 95	183.0	89.5	–	–	49.0	31.0	22.0	–	–	18.0	9
Nimonic 100	–	–	–	–	–	–	–	–	–	–	9
Cast Ni-based alloy:											
GUY	140.0	–	99.5	–	–	–	–	–	–	–	11
95 M-255	–	–	–	–	–	–	–	–	–	–	11
GMR 235	–	–	–	–	–	–	–	–	–	–	12
Wrought Fe-based alloy:											
G 42 B	120.0	64.0	–	–	–	31.2	22.3	–	–	21.1	13
G 40	107.0	–	–	–	–	–	–	–	–	–	14
Wrought Co-based alloy:											
G 32	148.0	86.0	–	–	21.0	32.4	25.3	–	–	23.6	15
S 816	–	–	77.5	59.5	–	–	–	–	–	–	22
Cast Co-based alloy:											
G 34	89.5	–	–	–	–	32.0	23.2	–	–	21.0	16
422-19	120.0	–	64.0	49.0	–	25.0	–	25.6	17.3	–	23
X 40	128.0	–	59.6	48.6	–	27.0	–	19.3	19.0	–	23
H.S.36	94.7	–	65.7	–	–	–	–	–	–	–	23
73 J	110	–	–	–	–	–	–	–	–	–	17
111 VT2-2	120.0	–	–	–	–	–	–	–	–	–	18
100 NT2	–	–	–	–	–	–	–	–	–	–	18
Sintered Vitallium	99.5	–	–	47.0*	–	–	–	–	–	–	19

* 850°C.

TABLE V (cont'd)

Material Designation	Tensile strength, x 10⁻³ p.s.i. at					Young's Modulus x 10⁻⁶ p.s.i. at					Ref.
	20°C	800°C	816°C	871°C	900°C	20°C	800°C	816°C	871°C	900°C	
Cast Cr-based alloys:											
60 Cr/15 Fe/25 Mo	-	-	-	-	-	37.0	-	-	-	-	4
60 Cr/25 Fe/15 Mo	-	-	-	-	-	37.0	-	-	-	-	4
Molybdenum (as rolled)	102	-	-	52	-	46	-	-	40	-	20
stress-relieved)	97.2	-	-	52.4	-	-	-	-	-	-	20
(recrystal-lised)	68.2	-	-	25.1	-	-	-	-	-	-	20
Tantalum	20/29	-	-	-	-	-	-	-	-	-	2
Tungsten	75	-	-	-	-	50	-	-	-	-	2
Chromium	-	-	-	-	-	36/37	-	-	-	-	2
Niobium	21/26	-	-	-	-	-	-	-	-	-	2

TABLE VI

Rupture stress data for metals and alloys

Material Designation	Density Gms/c.c	Rupture stress (×10⁻³ p.s.i.) at												Ref.
		816°C after			871°C after			982°C after			1093°C after			
		10 hrs	100 hrs	300 hrs	10 hrs	100 hrs	300 hrs	10 hrs	100 hrs	300 hrs	10 hrs	100 hrs	300 hrs	
Wrought Ni-based alloys														
Nimonic 90 (I)*	8.27	-	28.0	22.8	-	15.6	12.3	-	-	-	-	-	-	9
Nimonic 90 (II)‡	8.27	43.2	31.1	25.7	29.2	20.0	15.5	6.5	4.6	2.9	-	-	-	24
Inconel X 550	8.44	-	34.0	27.5	-	18.0	14.5	-	3.3	-	-	-	-	10
Nimonic 95	8.11	-	32.2	26.4	-	21.2	16.6	-	-	-	-	-	-	9
Inco 739	8.40	-	34.0	27.0	-	19.0	15.2	-	5.3	-	-	-	-	10
Waspaloy	8.40	-	31.5	-	-	19.5	-	-	-	-	-	-	-	10
M.252	8.40	-	29.0	23.5	-	16.0	13.0	-	-	-	-	-	-	10
Nimonic 100	8.04	-	42.55	35.85	-	26.9	21.3	-	7.85	6.7	-	-	-	9
Inco 700	8.00	-	42.0	36.0	-	28.0	23.5	-	6.5	-	-	-	-	10
Cast Ni-based alloys														
G3X	8.35	-	48.8	-	-	-	-	-	-	-	-	-	-	11
95M ~ 255	8.0	-	39.9	-	-	-	-	-	-	-	-	-	-	11
GMR235	8.45ƒ	-	57	-	-	25	-	-	11	-	-	-	-	12

* Supplier's data

‡ N.P.L. data

ƒ Density calculated from chemical composition

TABLE VI (cont'd)

Material Designation	Density Gms/c.c	Rupture stress (x10⁻³ p.s.i.) at												Ref.
		816°C after			871°C after			982°C after			1093°C after			
		10 hrs	100 hrs	300 hrs	10 hrs	100 hrs	300 hrs	10 hrs	100 hrs	300 hrs	10 hrs	100 hrs	300 hrs	
Wrought Fe-based alloys														
G42B	8.23	-	29.7	25.7	-	20.0	16.1	-	(10.0)	-	-	-	-	13
GAO	8.02	-	29.6	26.0	-	19.5	16.0	-	6.0	4.4	-	-	-	14
Wrought Co-based alloys														
G32	8.26	35.6	28.7	25.0	27.2	19.0	16.3	10.5	6.9	5.6	-	-	-	15
S816	8.91	-	24.0	20.9	-	14.0	11.9	-	5.5	4.4	-	-	-	10
Cast Co-based alloys														
G34*#	8.19	-	25.9	22.6	23.5	18.2	15.9	10.5	7.8	6.1	-	-	-	16
422-19	8.50	-	28.6	25.2	-	15.8	15.2	-	10.0	8.9	-	-	-	10
X 40	9.25	-	28.4	26.0	-	21.0	19.5	-	11.3	10.6	-	-	-	10
H.S.36	10.25/	-	29.0	27.3	-	23.0	21.0	-	10.5	9.0	-	-	-	10
75J	8.47/	43.5	34.7	31.9	33.4	26.4	24.0	17.9	12.75	11.2	-	-	-	17
111 VT 2-2	8.56/	43.0	34.3	30.2	36.9	27.35	23.8	15.2	11.1	9.8	-	-	-	18
100 MT - 2	8.37/	40.5	30.5	27.1	34.9	26.0	23.0	18.8	13.6	11.4	-	-	-	18
Cast Cr-based alloys														
60 Cr/15 Fe/25Mo	7.87	-	-	-	-	30.0	-	-	-	-	-	-	-	4
60 Cr/25 Fe/15Mo	7.63	-	-	-	-	20.0	-	-	-	-	-	-	-	4

( ) extrapolated   * Supplier's data   # N.P.L. data

/ density calculated from chemical composition

TABLE VI (cont'd)

Material Designation	Density Gms/c.c	Rupture stress (×10⁻³ p.s.i.) at												Ref.
		816°C after			871°C after			982°C after			1093°C after			
		10 hrs	100 hrs	300 hrs	10 hrs	100 hrs	300 hrs	10 hrs	100 hrs	300 hrs	10 hrs	100 hrs	300 hrs	
Wrought Mo and alloys:														
Swaged Mo														
(vacuum-tested)*	10.22	—	—	—	35	31	—	26	22	—	20	15	—	20
(vacuum-tested)‡		—	—	—	19	16	—	15	12	—	12	-	—	20
0.24% Nb-Mo														
(vacuum-tested)*	10.20 ƒ	—	—	—	—	54	—	—	33	—	—	12	—	20
(vacuum-tested)‡		—	—	—	—	23	—	—	16	—	—	11	—	20
0.45% Ti-Mo														
(vacuum-tested) *	10.17 ƒ	—	—	—	—	66	—	—	53	—	—	24	—	20
(vacuum-tested) *	10.17	—	—	—	—	37	—	—	28	—	—	20	—	20
Niobium (annealed, helium-tested)	8.4	—	—	—	23.8	20.0	17.5	18.7	14.0	—	—	—	—	21

* stress-relieved

‡ recrystallised

ƒ density calculated from chemical composition

TABLE VII

Specific 100 hour rupture strength properties (relative to Nimonic 90) of metals and alloys

Material Designation	Density gms/c.c	Density of material / density of N 90	100 hr. rupture strength at 871°C x 10^{-3} p.s.i.	Specific 100 hr. rupture strength at 871°C x 10^{-3} p.s.i.	100 hr. rupture strength at 982°C x 10^{-3} p.s.i.	Specific 100 hr. rupture strength at 982°C x 10^{-3} p.s.i.
Wrought Ni-based alloys:						
Nimonic 90 (I)	8.27	1.00	15.6	15.6	-	-
Nimonic 90 (II)	8.27	1.00	20.0	20.0	4.6	4.6
Inconel X 550	8.44	1.02	18.0	17.6	3.3	3.24
Nimonic 95	8.11	0.98	21.2	21.6	-	-
Inco 739	8.40	1.015	19.0	18.7	5.3	5.22
Hagaloy	8.40	1.015	19.5	19.2	-	-
M 252	8.40	1.015	16.0	15.76	-	-
Nimonic 100	8.04	0.97	26.88	27.7	7.84	8.1
Inco 700	8.00	0.97	28.0	28.8	6.5	6.7
Wrought Fe-based alloys:						
G 42 B	8.23	0.995	20.0	20.1	(10.0)	(10.1)
G 40	8.02	0.97	19.5	20.1	6.0	6.2
Wrought Co-based alloys:						
G 32	8.26	1.00	19.0	19.0	6.9	6.9
S 816	8.91	1.077	14.0	13.0	5.5	5.1
Cast Ni-based alloys:						
GMR235	8.45	1.022	25.0	24.5	11.0	10.75

(For footnotes see next page)

TABLE VII (cont'd)

Material Designation	Density gms/c.c	Density of material / density of N 90	100 hr. rupture strength at 871°C x 10⁻³ p.s.i.	Specific[#] 100 hr. rupture strength at 871°C x 10⁻³ p.s.i.	100 hr. rupture strength at 982°C x 10⁻³ p.s.i.	Specific[#] 100 hr. rupture strength at 982°C x 10⁻³ p.s.i.
Cast Co-based alloys:						
G 34	8.19	0.99	18.2	18.4	7.8	7.9
422-19	8.50	1.028	15.8	15.4	10.0	9.73
I 40	9.25	1.118	21.0	18.8	11.3	10.1
BS 36	10.25 f	1.24	23.0	18.55	10.5	8.47
7.3 J	8.47 f	1.025	26.4	25.75	12.75	12.45
111 VT 2-2	8.56 f	1.035	27.35	26.4	11.1	10.7
100 MT 2	8.37 f	1.01	26.0	25.7	13.57	13.5
Cast Cr-based alloys:						
60Cr/15Fe/25Mo	7.87	0.953	30.0	31.5	--	--
60Cr/25Fe/15Mo	7.63	0.926	20.0	21.6	--	--
Wrought Mo and alloys:						
Swaged Mo*	10.22	1.235	31.0	25.1	22.0	17.8
0.24% Nb–Mo*	10.20 f	1.23	54.0	43.9	33.0	26.8
0.45% Ti–Mo*	10.17 f	1.22	66.0	54.1	53.0	43.4
Wrought Niobium (annealed)	8.4	1.015	20.0	19.7	14.0	13.8

* rupture-tested in vacuum, stress-relieved

( ) extrapolation   f density calculated from chemical composition

specific rupture strength = $\dfrac{\text{laboratory rupture strength}}{\text{density of material/density of Nimonio 90}}$

TABLE VIII

Creep properties of metallic alloys

Material Designation	Test Temp. °C.	Stress (p.s.i. x 10^{-3}) for 0.1% creep in		Stress (p.s.i. x 10^{-3}) for 0.5% creep in		Ref.
		100 hours	300 hours	100 hours	300 hours	
Nimonic 90	815	17.2	11.85	24.0	18.6	9
	870	10.5	7.15	13.9	10.55	
Nimonic 95	815	24.8	19.9	31.0	25.0	9
	870	15.7	11.4	19.7	15.0	
Nimonic 100		NO	DATA			
G 42 B	800	14.8	11.2	–	–	13
	870	–	–	15.45	9.0	
G 32	800	23.3	20.8	29.5	26.4	15
	870	(14.5)	(11.5)	(19.5)	(15.5)	
G 34	815	10.5	–	18.8	15.4	16
	870	9.85	–	13.6	11.4	
422—19	815	–	–	14.4	–	24
	870	–	–	12.7	–	
X 40	815	10.70	–	16.8	–	25
	870	7.60	–	–	–	

( ) extrapolation

TABLE IX

Comparative fatigue strength data (Wohler) for creep resistant alloys

Material Designation	Temp. °C	No. of cycles x 10^{-6}	Fatigue Strength t.s.i.	x 10^{-3} p.s.i.	Ref.
Nimonic 90	815	45	0 ± 17.7	0 ± 39.6	9
	870	45	0 ± 12.2	0 ± 27.3	
Nimonic 95	815	45	0 ± 20.4	0 ± 45.5	9
	870	45	0 ± 16.8	0 ± 37.6	
G 42 B	800	40	0 ± 16	0 ± 35.8	13
	870	40	0 ± 14	0 ± 31.4	
G 40	800	40	0 ± 13.25	0 ± 29.6	14
	800	100	0 ± 11.25	0 ± 25.2	
	900	40	0 ± 12	0 ± 26.8	
	900	100	0 ± 10.75	0 ± 24.0	
G 32	800	40	0 ± 16	0 ± 35.8	15
G 34	800	100	0 ± 11	0 ± 24.6	16

TABLE X

Comparative fatigue and rupture strength properties of creep resistant alloys

Material Designation	Test Temp. °C	Fatigue Strength $\times 10^{-3}$ p.s.i. at 40 or 45 $\times 10^6$ cycles (300 hours)	Rupture Strength $\times 10^{-3}$ p.s.i. in 300 hours	$\dfrac{\text{Fatigue strength}}{\text{Rupture strength}}$, 300 hour life	Ref.
Nimonic 90	815 870	0 ± 39.6 0 ± 27.3	22.8 12.3	1.74 2.22	9
Nimonic 95	815 870	0 ± 45.5 0 ± 37.6	26.4 16.6	1.725 2.26	9
G 42 B	800 870	0 ± 35.8 0 ± 31.4	28.0 16.1	1.28 1.95	13
G 40	800 900	0 ± 29.6 0 ± 26.8	30.2 15.4	0.98 1.74	14
G 32	800	0 ± 35.8	27.7	1.29	15
G 34	800	0 ± 24.6	25.0	0.985	16

TABLE XI

Chemical Composition of Ceramics and Cermets

Material Designation	Nominal Chemical Composition, % by weight														Ref.
	Al_2O_3	SiO_2	ZrO_2	BeO	TiC	solid solution of Ti/Nb/Ta carbides	Cr_2C_3	Ni	Cr	Mo	Co	Fe	Si	Others	
Oxides:															
4811C	4	–	2	90	–	–	–	–	–	–	–	–	–	4 CaO	51
Ceramic 353	11	–	27	46	–	–	–	–	–	–	–	–	–	27 MgO	51
Sillimanite	60	40	–	–	–	–	–	–	–	–	–	–	–	–	51
Metal bonded carbides:															
WZ1	–	–	–	–	60	–	–	32	8	–	–	–	–	–	52
WZ2	–	–	–	–	60	–	–	–	12	–	28	–	–	–	52
WZ 120	–	–	–	–	50	–	–	30	10	–	10	–	–	–	52
40 N	–	–	–	–	54	–	–	40	–	–	–	–	–	–	53
P.S. 27	–	–	–	–	43	–	6	50	–	–	–	–	–	–	54
P.T.A.	–	–	–	–	80	–	7	–	–	–	20	–	–	–	55
K 138A	–	–	–	–	67	15	–	–	–	–	18	–	–	–	56
K 151A	–	–	–	–	67	15	–	18	–	–	–	–	–	–	56
K 152B	–	–	–	–	62	8	–	30	–	–	–	–	–	–	56
K 161B	–	–	–	–	72	8	–	16.7	–	3.3	–	–	–	–	56
K 162B	–	–	–	–	62	8	–	25	–	5	–	–	–	–	56
K 163B	–	–	–	–	57	8	–	30	–	5	–	–	–	–	56
M1809	–	–	–	–	52	8	–	30	–	10	–	–	–	–	57
M1813	–	–	–	–	52	8	–	33	–	7	–	–	–	–	57
M1590	–	–	–	–	70	–	–	–	–	–	–	27	3	–	57
TC-63-H	Titanium carbide infiltrated with Hastelloy C (60 Ni-15 Cr-15 Mo-5W-5 Fe)														40
TC-66-I	Titanium carbide infiltrated with Inconel (73 Ni-15Cr-7 Fe)														40

TABLE XII

Source and method of manufacture of ceramics and cermets considered useful for gas turbine blading

Material Designation	Source	Method of Manufacture
Oxides:		
4811 C Ceramic 353 Sillimanite	National Bureau of Standards, U.S.A.*	} Pressed and sintered
Carbides:		
Silicon Carbide (Niafrax) (Niafrax)	Carborundum Co. Ltd., Manchester	Not known
Metal/Oxides:		
30% Cr-Al$_2$O$_3$	Ohio State University*	Pressed and sintered
72% Cr-Al$_2$O$_3$	Ohio State University*	Pressed and sintered
79% Cr-Al$_2$O$_3$	Haynes Stellite Division of Union Carbide & Carbon Co., U.S.A.	Pressed and sintered
52% Cr-13% Mo-Al$_2$O$_3$	Ohio State University*	Pressed and sintered
Metal-bonded carbides:		
WZ 1 WZ 2 WZ 12C	Metallwerk Plansée, Reutte, Tyrol, Austria.	} Pressed and sintered
40 N	Metro-Cutanit Ltd., Warrington, Lancs	
F.S. 27	Hard Metal Tools Ltd., Coventry & Firth-Sterling Ltd., Pittsburg	Pressed and sintered
P.T.A.	Production Tool Alloy, Ltd., Bedford	Hot pressed

*Non-commercial source

TABLE XII (Cont'd)

Material Designation	Source	Method of Manufacture
Metal-bonded carbides:		
K.138A		
K.151A		
K.152B		
K.161B	Kennametal Corporation, Latrobe, Penn.	Pressed, or extruded and sintered
K.162B		
K.163B		
M.1809		
M.1590		
TC-63-H	Sintercast Corporation, Yonkers, N.Y.	Pressed, sintered and infiltrated
TC-66-I		
Molybdenum disilicide	N.A.C.A., and Plessey Co. Ltd., Towcester, Northants.	Hot pressed
15% Ni-CrB	G.E.C., U.S.A.	Hot pressed
Zr Boride 101		
Cr Boride 301		
Cr Boride 302	American-Electro-Metals Corporation, Yonkers, N.Y.	Unknown
Cr Boride 303		
Cr Boride 304		
Nickel aluminide		

TABLE XIII

Physical property data for ceramics and cermets

Material Designation	Density gms/c.c.	Mean Thermal Expansion, μ in/°C x 10^6 at					Thermal Conductivity, c.g.s. at				Ref.
		20/100°C	20/600°C	20/800°C	20/1000°C	20/1350°C	25°C	200°C	800°C	1000°C	
Oxides:											
Alumina	3.97	6	7**	–	9	–	–	0.06	0.02	–	58
Beryllia	3.00	8	8**	–	9	–	–	0.40	0.06	0.045	58
Zirconia	6.27	11	13**	–	15	–	–	0.0045	0.005	–	58
Thoria	9.69	8	9**	–	9	–	–	0.02	0.0085	0.0075	58
Magnesia	3.4/3.5	11	13**	–	15	–	–	0.07	0.02	0.018	58
Fused silica	2.21	0.5	0.57	–	0.58	–	0.0025	–	0.0045	0.0055	59,60
Zircon	–	–	4.0	–	–	–	–	0.014	0.01	–	57,61
4811 C	3.0	–	–	–	–	–	–	–	–	–	28
Ceramic 353	4.4	–	–	–	–	–	–	–	–	–	28
Sillimanite	2.77	–	–	–	–	–	–	–	–	–	28
Metal/Oxides:											
30% Cr-Al$_2$O$_3$	4.62	–	–	8.65	–	9.45	0.012	–	–	–	30
72% Cr-Al$_2$O$_3$	5.90	–	–	–	–	10.53	–	–	–	–	31
79% Cr-Al$_2$O$_3$	6.0	–	–	–	8.4	–	0.12	–	–	–	34
52% Cr-13% Mo -Al$_2$O$_3$	5.90	–	–	8.15	–	10.80	–	–	–	–	32
Carbides:											
Tungsten carbide	15.77	5.0/7.0	7.4	–	–	–	0.041	–	–	–	58
Titanium carbide	4.94	–	7.4	–	–	–	0.049	–	–	–	61
Zirconium carbide	6.30	–	6.75	–	–	–	–	–	–	–	61
Silicon carbide (Niafrax)	2.8	4.4	–	4.0	–	–	–	–	0.04	–	44
SiC/Si	2.7 (approx)	–	–	–	–	–	–	–	–	–	43

* 20/500°C   x 260°C

TABLE XIII (Cont'd)

Material Designation	Density gms/c.c.	Mean Thermal Expansion, in/in/°C x 10^6 at					Thermal Conductivity, c.g.s. at				Ref.
		20/100°C	20/600°C	20/800°C	20/1000°C	20/1350°C	25°C	200°C	800°C	1000°C	
Graphite	1.67	1.0/1.6	-	-	-	-	0.05/1.0	-	0.10	-	62
Metal-bonded carbides:											
WZ 1	6.2	-	6.9	-	-	-	-	-	-	-	52
WZ 2	6.1	-	7.0	-	-	-	-	-	-	-	52
WZ 12 C	6.6	-	8.6	-	-	-	-	-	-	-	52
40 N	6.15	5.6	9.1	9.5	9.9	-	0.052	-	-	0.071	53
FS 27	6.55	12.3	-	11.4	-	-	-	-	-	-	54
P.T.A.	5.4	-	8.6	-	9.9	-	-	-	-	-	55
K 138 A	5.8	-	8.1	-	-	-	0.075	-	-	-	56
X 151 A	5.8	-	7.7	-	-	-	-	-	-	-	56
K 152 B	6.0	-	-	-	-	-	0.077	-	-	-	56
K 161 B	5.7	-	9.5	-	-	-	-	-	-	-	56
K 162 B	6.0	-	9.7	-	-	-	0.072	-	-	-	56
K 163 B	6.2	-	-	-	-	-	-	-	-	-	56
TC-66-I	6.2	-	5.5	-	6.0	-	0.063	-	-	-	40
MoSi$_2$	6.2	-	-	-	8.0	-	-	-	-	-	50
Zr boride 101	5.3	-	4.8	-	-	5.8**	-	-	-	-	46
Cr boride 301	6.2	9.81	-	-	-	-	-	-	-	-	46
Ni aluminide Grade 1505	5.9	14.4	-	-	-	-	-	-	-	-	46

** 20/1200°C.

TABLE XIV

Data on tensile strength and Young's modulus of ceramics and cermets

Material Designation	Tensile Strength x 10^{-3} p.s.i. at						Young's Modulus x 10^{-6} p.s.i. at		Ref.
	20°C	816°C	871°C	982°C	1093°C	1200°C	20°C	800°C	
Oxides:									
Alumina	36	–	–	–	–	18	52	50	58
Beryllia	14	–	–	–	–	0.63	45	28	58
Zirconia	18	–	–	6.0	–	–	36	18	58
Thoria	–	–	–	–	–	–	21	18	58
Magnesia	3	–	–	3.1	–	–	12	–	58, 61
Fused Silica	7	–	–	–	–	–	9.7	–	59, 60
Zircon	–	–	–	6.2	–	3.0	–	–	61
Ceramic 353	–	–	–	–	–	–	–	–	28
Sillimanite	11.05	–	–	19.0	–	–	20.3	–	28
4811 C	–	–	–	19.0	–	–	20.6	–	28
Metal/Oxides:									
30% Cr-Al$_2$O$_3$	35.0	–	21.56	–	18.5	–	52.3	–	30
72% Cr-Al$_2$O$_3$	38.92	–	–	23.5	21.7	18.9	47.2	–	31
79% Cr-Al$_2$O$_3$	–	–	–	17.5	–	–	–	–	34
28% Cr-72Mo-Al$_2$O$_3$	53	–	40.35	28.5	25.0	–	45	–	32
Graphite	3.0	3.3	–	–	–	3.8	1.0	1.1	62
Carbides:									
Tungsten Carbide	–	–	–	50	–	–	102.5	–	58
Titanium Carbide	–	–	–	16.5	–	8.7	45	–	58, 28
Zirconium Carbide	–	–	–	13.1	–	14.4	–	–	28
Silicon Carbide ('Niafrax')	20	–	–	–	–	–	–	–	44
SiC/Si	–	6.0**	–	–	–	–	–	–	43

** at 800°C.

TABLE XIV (Cont'd)

Material Designation	Tensile Strength x 10^{-3} p.s.i. at						Young's Modulus x 10^{-6} p.s.i. at		Ref.
	20°C	816°C	871°C	982°C	1093°C	1200°C	20°C	800°C	
Metal-bonded carbides:									
WZ 1	-	85.0	-	32/41.6	-	-	-	-	52
WZ 2	-	-	-	32	-	-	-	-	52
WZ 12C	46.5/51.5	-	-	-	-	-	50.85	-	52
40 N (FS 26)	75	52	-	41	-	-	-	-	53
FS 27	84	60	-	35	-	-	-	-	54
P.T.A.	-	-	47	25.8	-	-	55.0	-	55
K 138A	150	-	-	100	36.2	18.5	57.3	-	56
K 151A	-	-	-	-	38.1	18.8	57.0	-	56
K 152B	100	-	-	-	-	-	47.0	-	56
K 161B	76	-	-	-	-	-	60.0	-	56
K 162B	115	-	-	-	-	-	59.0	-	56
K 163B	130	-	-	-	-	-	56.0	-	56
TC-66-I	-	-	-	50	-	-	-	40*	40
MoSi$_2$	-	-	-	-	-	-	59.0	-	50
Zr Boride 101	-	-	-	35/40	-	-	31.6	24*	46
Cr Boride 301	-	-	-	-	-	-	-	-	46
Ni aluminide Grade 1505	-	-	-	-	-	-	-	-	46

* at 1000°C.

TABLE XV

Rupture stress data for ceramics and cermets

Material Designation	Density Gms/c.c	Rupture stress, x 10^{-3} p.s.i. at												Ref.
		816°C after			871°C after			982°C after			1093°C after			
		10 hrs	100 hrs	300 hrs	10 hrs	100 hrs	300 hrs	10 hrs	100 hrs	300 hrs	10 hrs	100 hrs	300 hrs	
Oxides:														
4811C	3.0	–	14.0	–	–	–	–	–	17.0	–	–	10.0 (min)	–	28,51
Ceramic 353	4.4	–	12.0	–	–	–	–	–	18.0	–	–	–	–	28,51
Sillimanite	2.77	–	11.5	–	–	9.6	–	–	5.3	–	–	–	–	28,51
Metal/oxides:														
30% Cr-Al₂O₃	4.60	–	–	–	–	–	–	16.5	16.25	16.0	–	13.6	–	30
72% Cr-Al₂O₃	5.90	–	–	–	–	–	–	19.0	16.8	14.5	–	8.6	–	31
52% Cr/15% Mo/Al₂O₃	5.90	–	–	–	–	–	–	25.0	21.9	20.5	11.2	7.0	–	32
Metal-bonded carbides:														
WZ1	6.1	–	43.0	38.7	–	32.1	28.9	–	14.6	11.2	–	–	–	52
WZ2	6.15	–	–	–	–	–	–	–	10.2	9.0	–	–	–	52
WZ 12o	6.6	–	–	24.0	–	20.2	16.4	–	14.0	–	–	–	–	63
4ON	6.15	–	–	–	–	–	–	–	11.1	8.4	–	–	–	53
F.S.27	6.55	–	–	–	–	–	–	14.2	9.5	7.2	–	–	–	54
K.138A	5.8	–	–	–	27.5	23.5	21.5	13.0	10.5	7.8	–	–	–	56
K.151A	5.8	–	–	–	21.0	15.0	12.5	15.5	11.5	9.25	–	–	–	56
K.152B	6.0	–	–	–	36.6	29.0	25.5	10.75	5.0	(3.0)	16.5	–	–	56
K.161B	5.7	–	–	–	–	–	–	20.0	15.5	12.5	–	3.2	–	64

( ) Extrapolation

TABLE IV (cont'd)

Material Designation	Density Gms/c.c	Rupture stress, x 10⁻³ p.s.i. at												Ref.
		816°C after			871°C after			982°C after			1093°C after			
		10 hrs	100 hrs	300 hrs	10 hrs	100 hrs	300 hrs	10 hrs	100 hrs	300 hrs	10 hrs	100 hrs	300 hrs	
Metal-bonded carbides:														
K.162B	6.0	–	–	–	42.5	31.5	27.5	20.5	15.5	12.5	–	–	–	64
K.163B	6.2	–	–	–	–	27.0	–	–	10.0	–	–	–	–	64
M.1809	6.4	–	–	–	–	34.5	–	–	12.5	–	–	–	–	58
M.1813	6.3	–	–	–	–	31.0	–	–	12.0	–	–	–	–	58
M.1590	5.7	–	–	–	22.5	16.5	13.5	9.0	5.0	3.0	–	–	–	58
TC-63-H	6.0	–	–	–	37.0	26.4	21.1	21.0	14.3	12.0	–	–	–	40
TC-66-I	6.2	–	–	–	52.0	38.0	32.0	22.0	15.0	12.5	–	–	–	40
Silicides:														
Mo Si₂	6.18	–	–	–	–	35.0	–	–	16.3	–	–	10.0	–	47,48
Bonded borides:														
Zr Boride 101	5.3	–	–	–	–	–	–	25.0	18.5	(16.2)	–	–	–	46
15% Ni/CrB	5.9	6.0	4.9	–	4.0	2.7	–	–	–	–	–	–	–	46
Cr Boride 301	6.2	–	–	–	–	–	–	–	28.0	–	–	–	–	46
Cr Boride 302	6.67	–	–	–	–	–	–	–	18.0	–	–	–	–	46
Cr Boride 303	6.75	–	–	–	–	–	–	–	15.0	–	–	–	–	46
Cr Boride 304	6.77	–	–	–	–	–	–	–	12.0	–	–	–	–	46
Aluminides:														
Nickel aluminide(1505)	5.80	–	–	–	–	–	–	–	12.0	–	–	–	–	46

( ) Extrapolation

TABLE XVI

Specific 100 hr. rupture strength properties (relative to Nimonic 90) of ceramics and cermets

Material Designation	Density gms/c.c	Density of material / density of N 90	100 hr. rupture strength at 871°C x 10^{-3} p.s.i.	Specific# 100 hr. rupture strength at 871°C x 10^{-3} p.s.i.	100 hr. rupture strength at 982°C x 10^{-3} p.s.i.	Specific# 100 hr. rupture strength at 982°C x 10^{-3} p.s.i.
Oxides:						
4811 C	3.0	0.363	-	-	17.0	46.8
Ceramic 353	4.4	0.531	-	-	18.0	33.9
Sillimanite	2.77	0.335	9.6	28.66	5.5	16.4
Metal/oxides:						
30%Cr-Al$_2$O$_3$	4.60	0.555	-	-	16.25	29.5
72%Cr-Al$_2$O$_3$	5.90	0.715	-	-	16.8	23.6
52%Cr/17%Mo/Al$_2$O$_3$	5.90	0.715	-	-	21.9	30.6
Metal-bonded carbides:						
WZ 1	6.1	0.738	32.1	43.5	14.6	19.8
WZ 2	6.15	0.744	-	-	10.2	13.7
WZ 12 C	6.6	0.80	-	-	14.0	17.5
LO N	6.15	0.738	20.16	27.3	11.1	15.0
F.S. 27	6.55	0.79	-	-	9.5	12.0
K 138 A	5.8	0.70	23.5	33.6	10.5	15.0
K 151 A	5.8	0.70	23.5	33.6	11.5	16.4
K 152 B	6.0	0.72	15.0	20.8	5.0	9.0
K 161 P	5.7	0.69	29.0	42.0	15.5	22.5
K 162 B	6.0	0.72	31.5	43.6	15.5	20.0
K 163 B	6.2	0.75	27.0	36.0	10.0	13.3

\# Specific rupture strength = $\dfrac{\text{laboratory rupture strength}}{\text{density of material/density of Nimonic 90}}$

TABLE XVI (cont'd)

Material Designation	Density gms/c.c	Density of material / density of N 90	100 hr. rupture strength at 871°C x 10^-3 p.s.i.	Specific* 100 hr. rupture strength at 871°C x 10^-3 p.s.i.	100 hr. rupture strength at 982°C x 10^-3 p.s.i.	Specific* 100 hr. rupture strength at 982°C x 10^-3 p.s.i.
Metal-bonded carbides:						
M 1809	6.4	0.73	34.5	47.2	12.5	17.1
M 1813	6.3	0.76	31.0	40.8	12.0	15.8
M 1590	5.7	0.69	16.5	24.0	5.0	7.25
TC-63-H	6.0	0.72	25.4	36.6	14.3	20.0
TC-66-I	6.2	0.75	38.0	50.7	15.0	20.0
Silicides:						
MoSi$_2$	6.18	0.75	35.0	46.6	16.3	21.8
Bonded borides:						
Zr Boride 101	5.3	0.64	-	-	18.5	29.0
Cr Boride 301	6.2	0.75	-	-	28.0	37.3
Cr Boride 302	6.67	0.81	-	-	18.0	22.2
Cr Boride 303	6.75	0.82	-	-	15.0	18.3
Cr Boride 304	6.77	0.82	-	-	12.0	14.7
Aluminides:						
Nickel aluminide (Grade 1505)	5.80	0.70	-	-	12.0	17.1

* Specific rupture strength = $\dfrac{\text{Laboratory rupture strength}}{\text{density of material/density of Nimonic 90}}$

TABLE XVII

Bend creep data on ceramics, cermets and Nimonic 95

Material designation	Temp. °C	Stress, x 10^{-3} p.s.i.	Time (hours) for mid-span deflection of 0.0235 in.*
Titanium carbide	1000	4.48	28.6
40 N	1000	4.48	8.8
K 163 B	1000	4.48	9.2
Carbometal	1000	4.48	79.0
"Nifrax" silicon carbide	1000	4.48	49.5
Fused silica (transparent)	1000	4.48	12.5
Molybdenum disilicide	1000	4.48	66.5
75% Cr-Al$_2$O$_3$ (Morgan Crucible Co.)	1000	4.48	93.0
79% Cr-Al$_2$O$_3$ (Haynes Stellite Co.)	1000	4.48	295.0
Nimonic 95	1000	4.48	4.4
40 N	900	4.48	39.0
K 163 B	900	4.48	148.0
Fused silica (transparent)	900	4.48	332.0
Nimonic 95	900	4.48	302.0
20% Cr-Al$_2$O$_3$ (Plessey)	1200	6.72	28.0
I.C. Silicon Carbide (Morgan Crucible Co.)	1200	6.72	12.75

* Equivalent to a tensile creep strain of 0.125%

TABLE XVIII

Data on oxidation resistance of ceramics and cermets

Material Designation	800°C		1000°C			1100°C			1200°C		Ref.
	100 hrs	500 hrs*	50 hrs	100 hrs	500 hrs*	50 hrs	100 hrs	500 hrs*	50 hrs	500 hrs*	
Metal/oxides:											
30%Cr-Al$_2$O$_3$	-	-	-	-	-	-	-	-	-	negligible	30
72%Cr-Al$_2$O$_3$	-	-	-	-	-	-	+2.0	-	-	-	31
52%Cr-17%Mo-Al$_2$O$_3$	-	-	-	-	-	-	+2.5	-	-	---	32
Carbides:											
Titanium carbide	-	+4.8	-	-	-	-	-	-	-	completely oxidised*	66
'Niafrax' SiC	-	-3.4	-	-	-	-	-	-	-	+1.1	66
Metal-bonded carbides											
WZ 1	-	-	+9.2	-	-	-	-	-	-	-	38
WZ 2	-	-	+8.45	-	-	-	-	-	-	-	38
WZ 12C	-	-	+32	-	-	+54	-	-	-	-	38,67
(c/f Nimonic 80A)	-	-	+18	-	-	+37	-	-	-	-	33,67
40 N	+11.1	+27.3	-	+28.7	+51.6	-	+72.8	-	-	completely oxidised*	66
K 138 A	-	-	-	-	-	-	+10	-	-	-	68
K 151 A	-	-	-	-	-	-	+17	-	-	-	68
K 163 B	-	+5.0	-	-	+48.0	-	-	-	-	completely oxidised*	66
TC-63-H	-	-	-	-	-	-	+22.5	-	-	-	40

*Reference 66, specimens 0.3 cms. thick

TABLE XVIII (cont'd)

Material Designation	Change in weight, mgms/cm² at										Ref.
	800°C		1000°C			1100°C			1200°C		
	100 hrs	500 hrs	50 hrs	100 hrs	500 hrs	50 hrs	100 hrs	500 hrs	50 hrs	500 hrs	
Mo Si$_2$	–	–	–	–	–	–	–	–	–	+0.2	50
Zr Boride 101	–	–	–	–	–	–	+6	–	–	–	46
Cr Borides 302, 303, 304	– –	– –	– –	– –	– –	– –	+2.5/3.0	– –	– –	– –	46
Nickel aluminide							+1.0/3.0				46

TABLE XIX

Thermal shock indices for ceramics and cermets

Material	Tensile strength* (σ) x 10⁻³ p.s.i.	Thermal conductivity (k)*** c.g.s.	Mean coefficient of thermal expansion xx ins/in/°C x 10⁶	Young's Modulus at 20°C x 10⁻⁶ p.s.i.	$\frac{\sigma}{\alpha E}$	$\frac{K\sigma}{\alpha E}$
Alumina	36.0	0.02	8	52	86.5	1.73
Beryllia	6.2	0.06	8.5	45	16.2	0.97
Zirconia	6.0	0.005	14	36	10.9	0.54
Magnesia	3.1	0.02	14	12	18.4	0.37
Fused silica	3.0	0.045	0.57	9.7	460	2.07
Zircon	6.2	0.01	4.0	18.2	85.1	0.85
30%Cr-Al₂O₃	19.0	0.01	8.65	52.3	42	0.42
79%Cr-Al₂O₃	17.5	0.04	8.4	47.2	44.1	1.76
Titanium carbide	16.5	0.041	7.4	45.0	50	2.03
80% TiC-20% Co	25.8	0.07	9.2	55	51	3.57

* Where possible, data at 982°C
*** Where possible, data at 800°C
xx Where possible, data at 20/800°C
x Data at 20°C

TABLE XX

Results of N.A.C.A. thermal shock tests on ceramics and cermets

Material Designation	No. of cycles prior to failure on cooling from:-				Velocity of cooling air ft/s.	Ref.
	982°C	1093°C	1205°C	1315°C		
TiC	{ 25	25	25	21	265	61
	{ 25	25	25	14	265	61
Boron carbide (B_4C) (hot pressed)	9	–	–	–	265	61
	3	–	–	–	265	61
85% SiC–15% B_4C	{ 25	6	–	–	265	61
	{ 25	25	2	–	265	61
Zirconium carbide (ZrC)	22	–	–	–	265	61
Zircon ($ZrO_2 \cdot SiO_2$)	1 ✴	–	–	–	265	61
Zirconia (ZrO_2)	✴	–	–	–	265	61
Beryllia (BeO)	25 ✴	3	–	–	265	61
Magnesia (MgO)	25 ✴	–	–	–	265	61
100% ZrB_2	25	13	25	13	265	46
Zr Boride 101	25	25	–	–	265	46
(97.5% ZrB_2–2.5% B)	{ 25	21	25	6	265	46
92.5% ZrB_2–2.5% B	{ 25	25	–	–	265	46
60% B_4C–40% TiB_2	3	4	–	–	265	46
$MoSi_2$	2	–	–	–	265	42
CrB 301	25	–	–	–	265	49
302	25	25	25	25	265	46
303	25	25	25	25	265	46
304	25	25	25	25	265	46
Ni aluminide, grade 1505	{ 25	25	25	25	265	46
	{ 25	25	25	22	265 φ	31
79% Cr–Al_2O_3	18	15	10	5	265 φ	31
K138A	25	25	25	–	495	56
K151A	25	25	25	3	495	56
80 TiC/20Co	25	25	25	25	495	61

✴ Failed during first heating

φ Mean of 6 tests at each cooling air velocity

TABLE XXI

Comparison of Laboratory Test Performance and Thermal Shock Indices of Ceramics and Cermets

Material	$\dfrac{K\sigma}{\alpha E}$	No. of cycles prior to failure on cooling from:				Velocity of Cooling Air ft/s
		982°C	1093°C	1205°C	1315°C	
80% TiC/20% Co	3.57	25	25	25	25	495
Titanium carbide	2.03	25 25	25 25	25 25	21 14	265 265
79% Cr–Al$_2$O$_3$	1.76	25 18	25 15	25 10	22 5	265 495
Beryllia	0.97	25	3	—	—	265
Zircon	0.85	1	—	—	—	265
Zirconia	0.54	$\frac{1}{2}$*	—	—	—	265
Magnesia	0.37	$\frac{1}{2}$*	—	—	—	265

*Failed during first heating cycle

TABLE XXII

Room temperature impact strength data for ceramics and cermets

Type of Machine	Type of Specimen	Material Designation	Impact Strength in in. lbs.	Impact Strength in in. lbs/in^2	Ref.
	Unnotched ½" dia.	Al$_2$O$_3$ Cast Iron Stellite 21 79% Cr-Al$_2$O$_3$	7 73 200 11	35 365 1000 55	34
Charpy Machine	Unnotched 10 mm. sq. section	Nickel aluminide, Grade 1505 60% TiC bonded with 40% (Ni-Cr-Co) TiC bonded with 50% (Ni-Cr-Co) i.e. WZ12C TiC bonded with 60% (Ni-Cr-Co)	48 32.4 48 84	310 210 310 540	68
	Unnotched ¼" dia. bar	30% Cr-Al$_2$O$_3$	1	20	30
Riehle Machine	Unnotched ⅜" dia. bar	K151A K138A 72% Cr-Al$_2$O$_3$	14.4/19.2 12.0/13.2 9.6/12.0	- - - - - - - - -	68
N.A.C.A. Drop Impact Testing Machine	Unnotched ¼" x 3/16" section	K1523 K162B FS27	2.1 3.3 1.29	- - - - - - - - -	72

TABLE XXII (Cont'd)

Type of Machine	Type of Specimen	Material Designation	Impact Strength in in. lbs.	Impact Strength in in. lbs/in^2	Ref.
N.A.C.A. Drop Impact Testing Machine	Notched ¼" x 3/16" section	K152B K162B FS27 X40	3.3 1.93 1.29 48.05	- - - -	54
	Unknown	Nickel aluminide X40	10/12 60	- - - - -	68
	Unknown	Zr Boride (Borolite I) Cr Boride (Borolite IV) Bonded Cr Boride (Borolite V)	<0.5 2 6/8	-	
Hounsfield Plastics Impact Testing Machine	Unnotched 0.11" sq. section	K163B 40N 79% Cr-Al$_2$O$_3$ 20% Cr-Al$_2$O$_3$ Fused silica* 'Niafrax' silicon carbide	1.0 0.65 0.29 0.12 0.24 0.05	- - - - - -	70

* 0.24 in. sq. section test specimen

TABLE XXIII

Variation of impact strength of ceramics and cermets with temperature

Type of Machine	Type of Specimen	Material Designation	Impact Strength, in in. lbs at				Ref.
			25°C	650°C	816°C	982°C	
Baldwin	Unnotched 10 mm. square section (Charpy)	4ON F.S.27	54 56.4	58.8 57.6	57.6 70.8	52.8 69.6	54
N.A.C.A. Drop Impact Test	Unnotched ¼" x 3/16"	K162B	6.3	2.6	–	–	69
	Notched ¼" x 3/16"	K162B F.S.27	3.3 1.29	1.3 1.45	– 1.34	– –	54

TABLE XXIV

Temperatures and stresses for 100-hour rupture life assuming each alloy to be under same centrifugal loading as Nimonic 90

Material Designation	100 hour rupture stress x 10⁻³ p.s.i.	Temp. °C.	100 hour rupture stress x 10⁻³ p.s.i.	Temp. °C.	100 hour rupture stress x 10⁻³ p.s.i.	Temp. °C	100 hour rupture stress x 10⁻³ p.s.i.	Temp. °C.
Nimonic 90	17.92	880	22.40	855	24.70	845	30.00	820
Nimonic 100	17.4	915	21.73	895	23.95	885	29.10	860
73 J	18.4	920	22.96	890	25.30	875	30.75	835
72% Cr-Al₂O₃ +	12.8	1035	16.02	995	17.65	982	21.45	982
52% Cr-13% Mo-Al₂O₃	12.8	1045	16.02	1025	17.65	1010	21.45	980
K 161 B	12.4	(995)	15.46	980	17.04	960	20.70	935
TC-56-I	13.4	(990)	16.80	970	18.51	960	22.50	935
Swaged Mo (stress-relieved)	22.2	980	27.55	900	30.36	870	36.90	⁻⁺
0.45% Ti-Mo (stress-relieved)	21.8	(1100)	27.50	1080	30.30	1065	36.85	1040
Wrought Niobium (annealed)	18.2	900	22.74	<871⁺	25.07	<871⁺	30.45	<871⁺

+ No 100 hour rupture data available below 871°C.

( ) Obtained by extrapolation of stress/temperature curve.

APPENDIX I

Chemical Symbols of Elements and Compounds

Chemical Symbol	Element or Compound
Al	Aluminium
Al_2O_3	Aluminium oxide
B	Boron
BeO	Beryllium oxide (beryllia)
C	Carbon
CaO	Calcium oxide
Co	Cobalt
Cr	Chromium
Cr B	Chromium boride
$Cr_2 C_3$	Chromium carbide
Fe	Iron
MgO	Magnesia
Mn	Manganese
Mo	Molybdenum
$MoSi_2$	Molybdenum disilicide
Nb	Niobium
Ni	Nickel
Si	Silicon
SiC	Silicon carbide
SiO_2	Silica
Ta	Tantalum
TaC	Tantalum carbide
ThO_2	Thorium oxide (thoria)
Ti	Titanium
TiC	Titanium carbide
V	Vanadium
W	Tungsten (wolfram)
WC	Tungsten carbide
Zr	Zirconium
ZrO_2	Zirconium oxide
$ZrO_2.SiO_2$	Zirconium silicate (zircon)

SK 21067

FIG.1.

STRESS, X 10³ P.s.i.

	NIMONIC 90
	INCONEL X550
	NIMONIC 95
	INCO 739
	WASPALOY
	M 252
	NIMONIC 100
	INCO 700

WROUGHT NICKEL-BASED ALLOYS

NO DATA — GUY
NO DATA — 95 M- 255
R- 235

CAST NICKEL-BASED ALLOYS

G 42 B — WROUGHT IRON-BASED

G 32
S 816

WROUGHT COBALT-BASED

G 34
422-19
X-40
H.S. 36
73 J
III VT2-2
100 NT 2

CAST COBALT-BASED ALLOYS

60 Cr/15 Fe/25 Mo
60 Cr/25 Fe/15 Mo

CAST CHROMIUM-BASED

WROUGHT Mo
54 X 10³ P.s.i. — 0.24% Nb - Mo
68 X 10³ P.s.i. — 0.45% Ti - Mo
NIOBIUM

Mo & ALLOYS (STRESS-RELIEVED)

STRESS, X 10³ P.S.i.
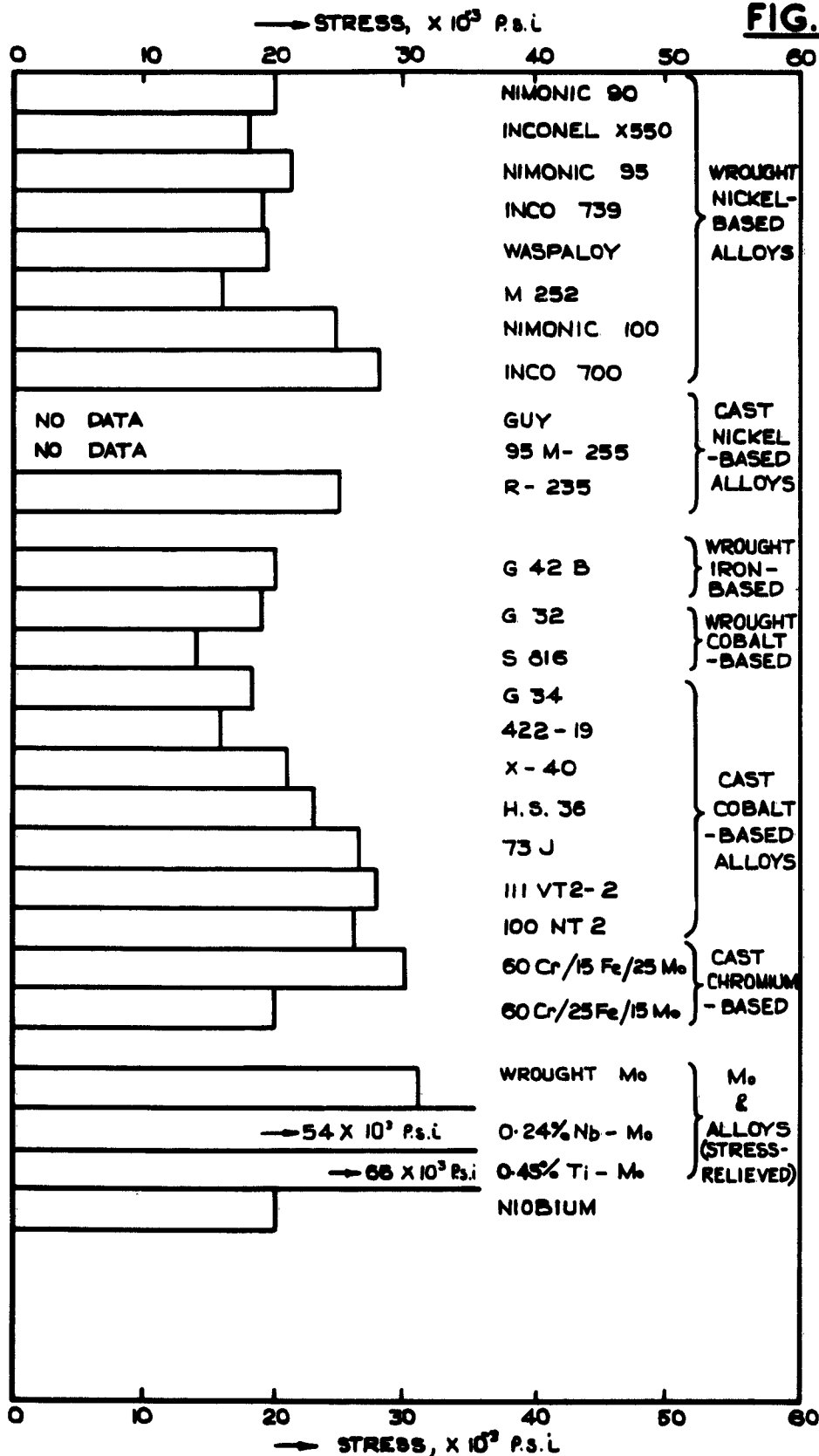
100 HOUR RUPTURE STRESS DATA AT 871 °C. FOR METALS AND ALLOYS

FIG. 2.
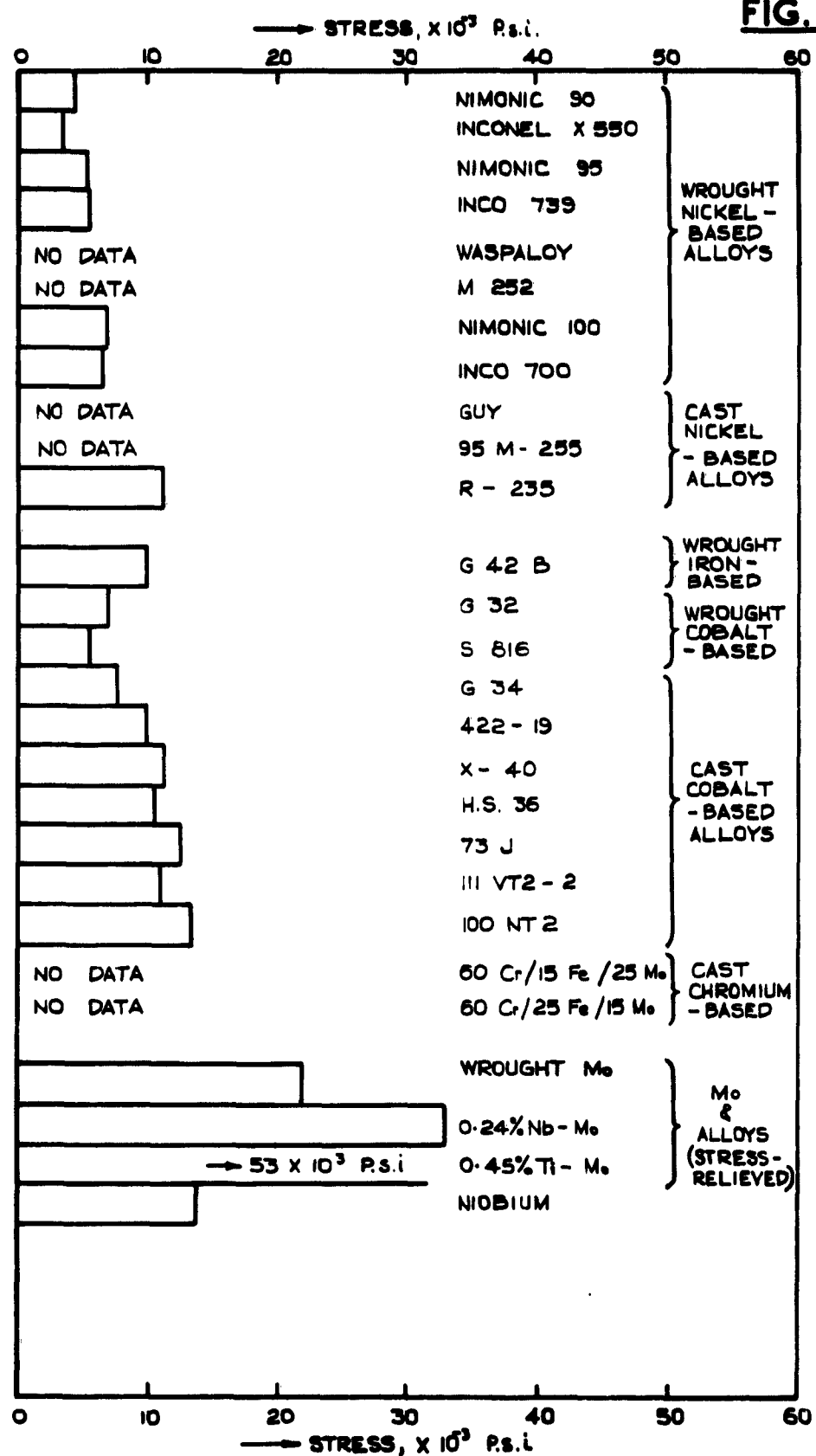
SK 21068

100 HOUR RUPTURE STRESS DATA AT 982 °C.
FOR METALS AND ALLOYS

FIG. 3.

100 HR - RUPTURE WROUGHT ALLOYS.
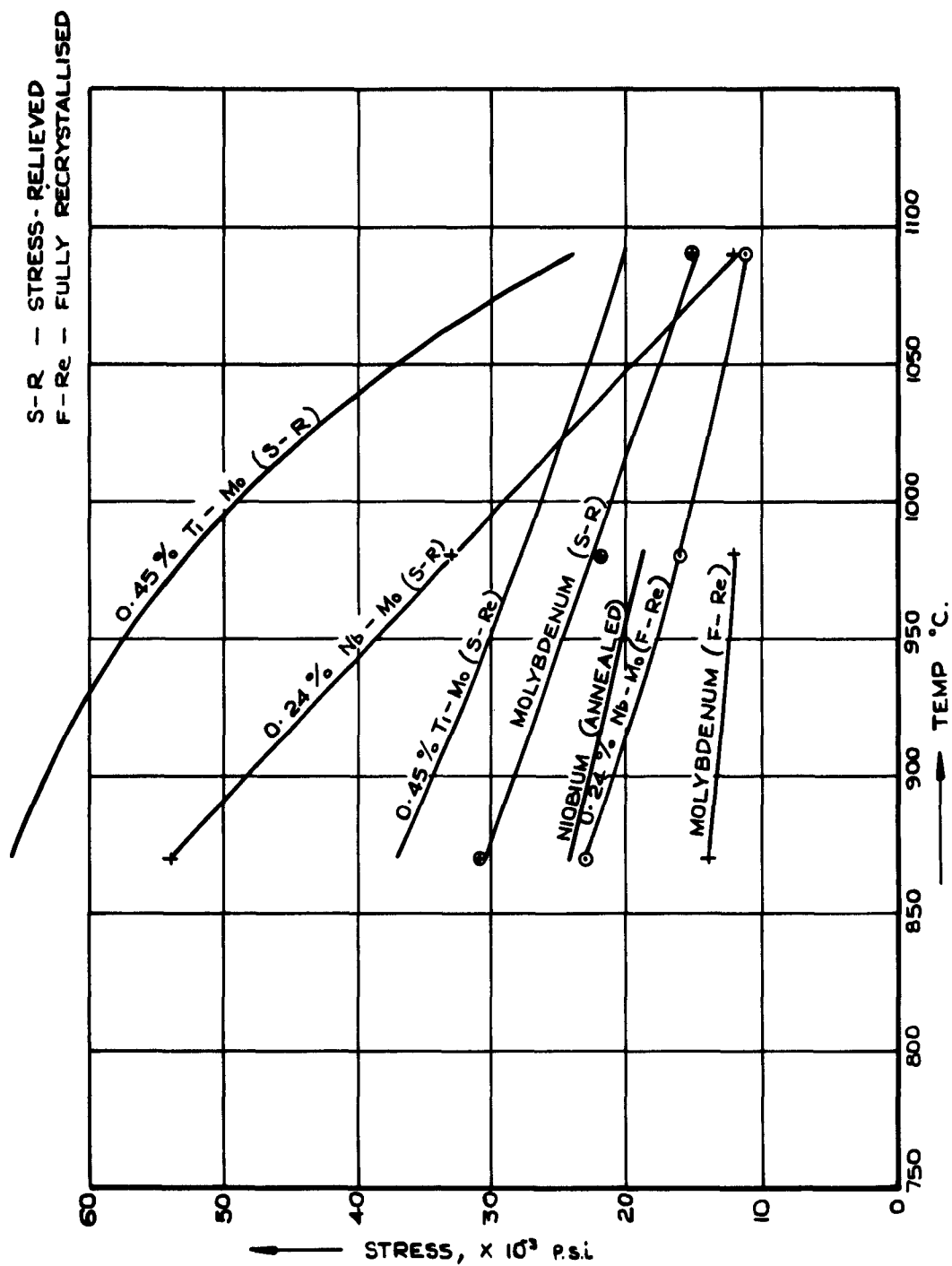STRESS DATA,

⊙ G 42B
+ N 90
✳ N 100
• G 32
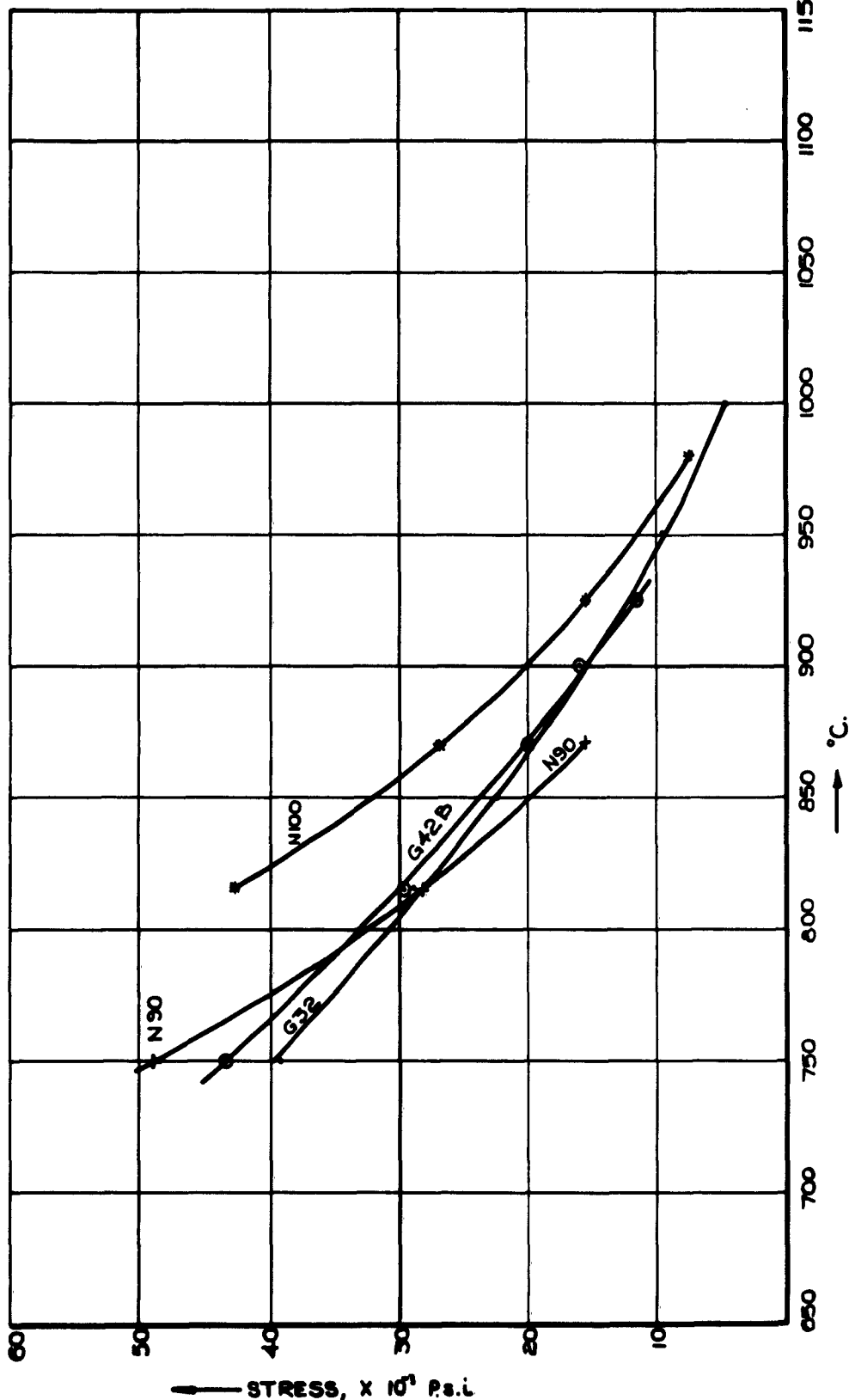
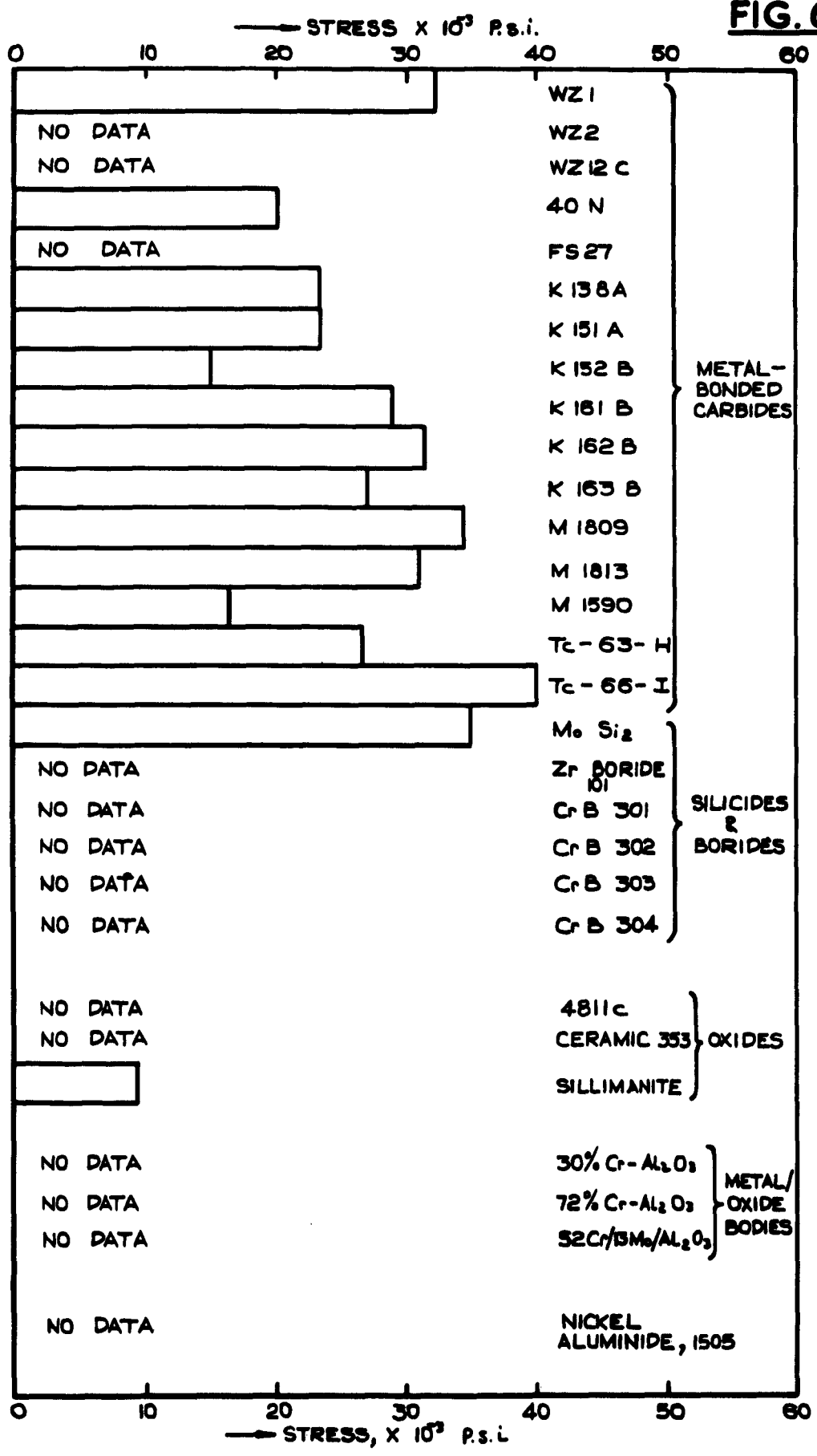100 HOUR RUPTURE STRESS / TEMPERATURE
CURVES FOR WROUGHT ALLOYS

FIG. 4.

SK 21070
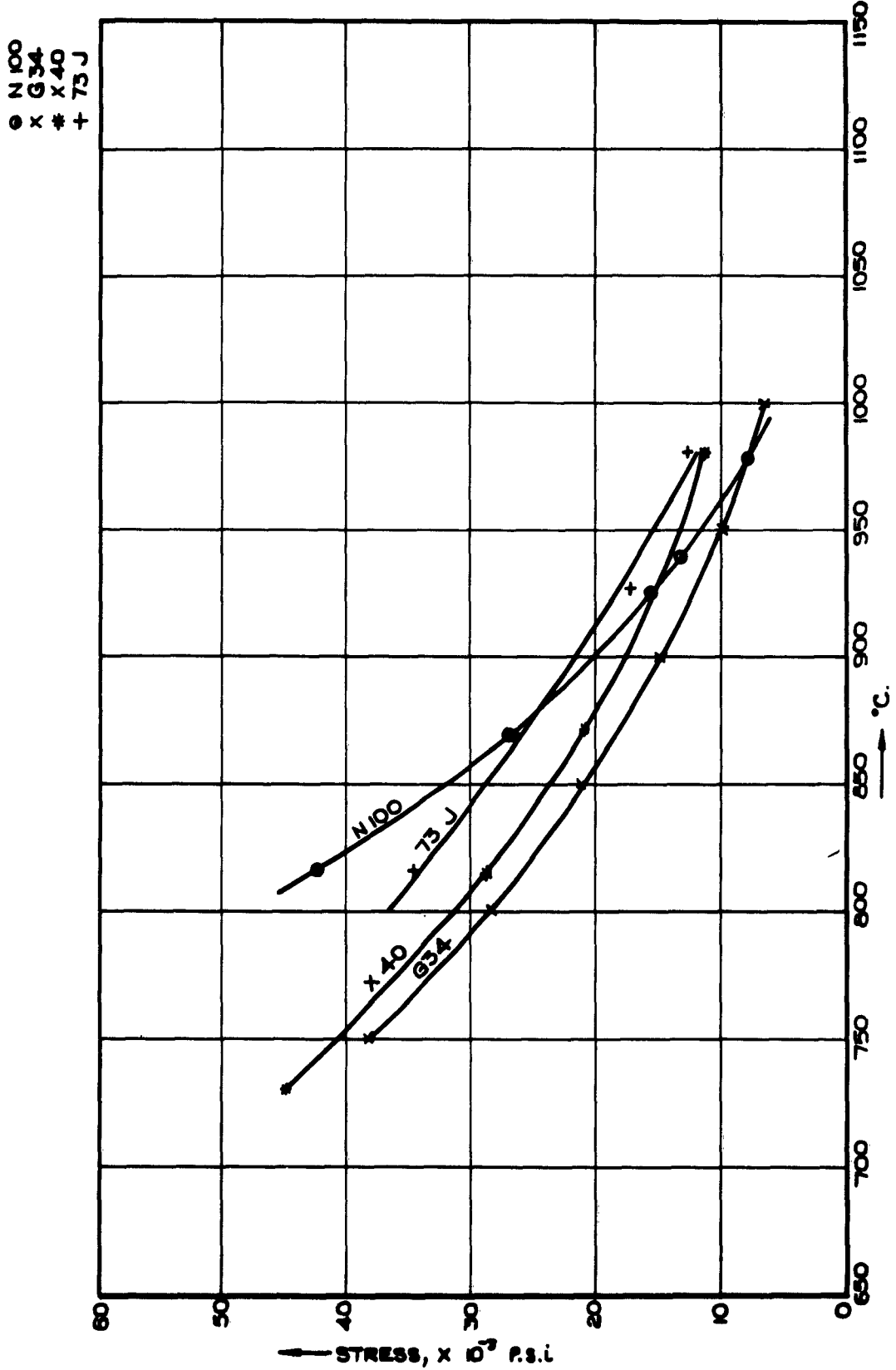
100 HOUR RUPTURE STRESS / TEMPERATURE
CURVES FOR CAST ALLOYS

100 HOUR RUPTURE STRESS/TEMPERATURE
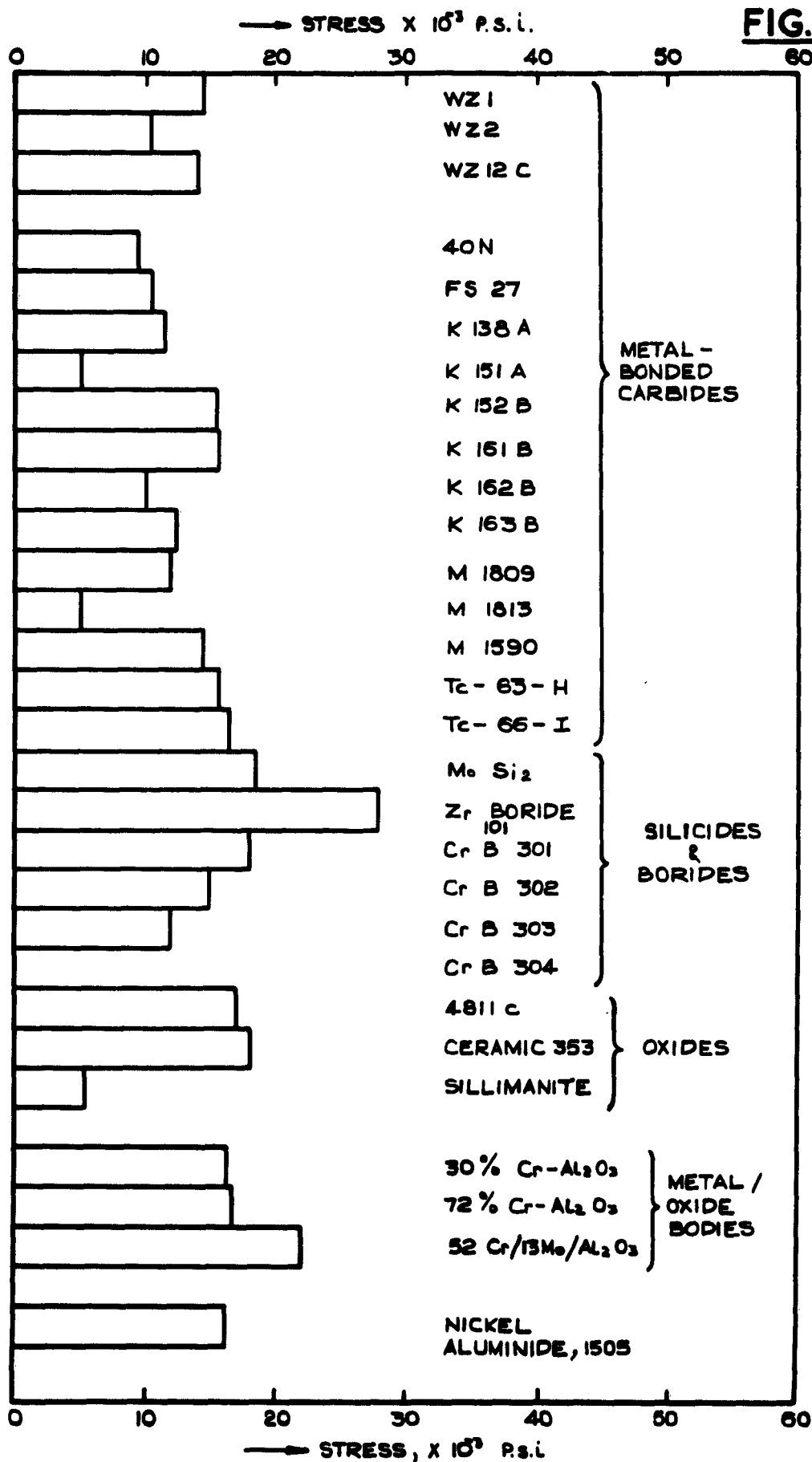CURVES FOR MOLYBDENUM AND
ITS ALLOYS AND NIOBIUM

FIG. 6.

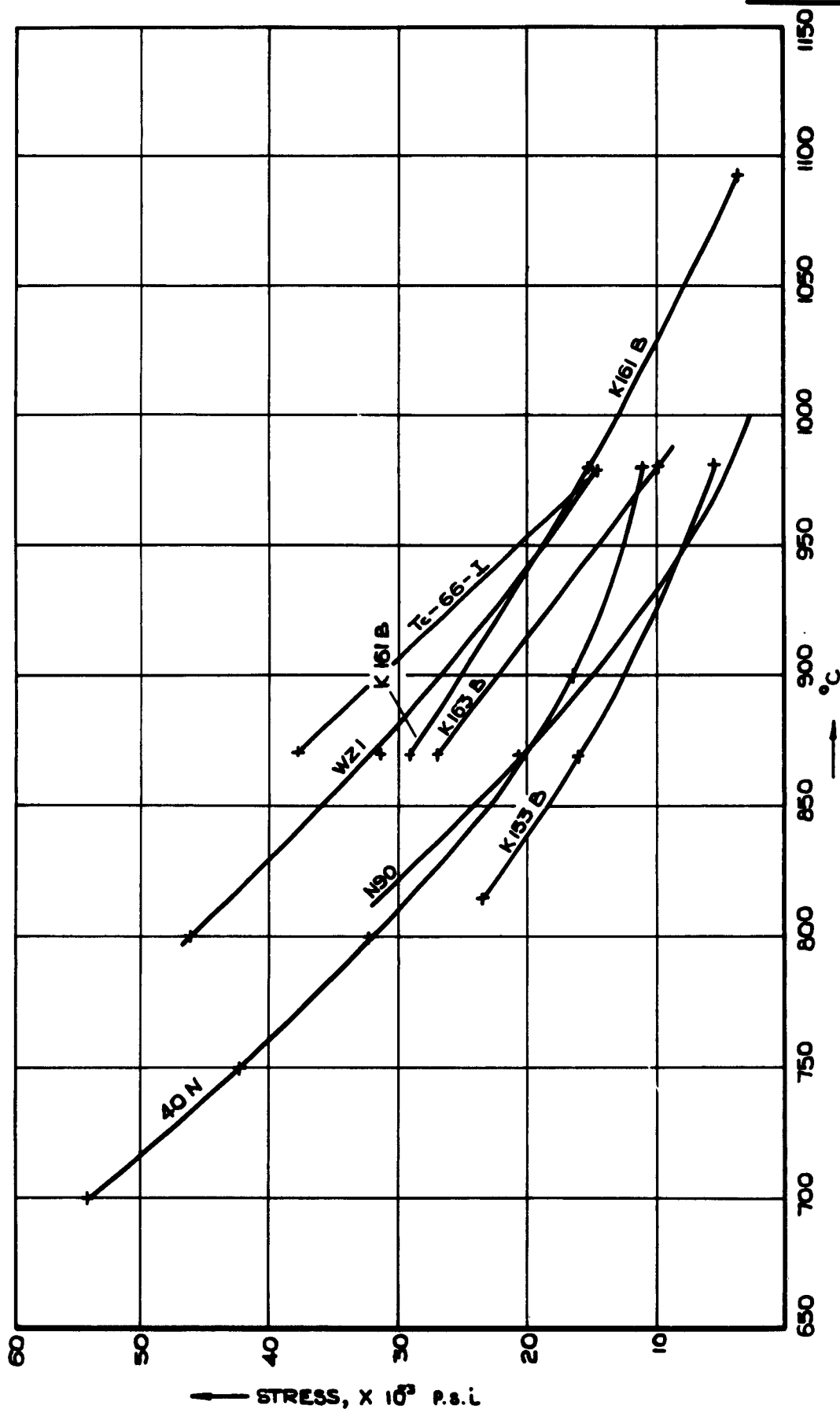100-HOUR RUPTURE STRESS DATA AT 871°C
FOR CERAMICS AND CERMETS

STRESS X 10³ P.s.i.

FIG. 7.

WZ 1	
WZ 2	
WZ 12 C	
40 N	
FS 27	
K 138 A	
K 151 A	METAL - BONDED CARBIDES
K 152 B	
K 151 B	
K 162 B	
K 163 B	
M 1809	
M 1813	
M 1590	
Tc - 63 - H	
Tc - 66 - I	
Mo Si₂	
Zr BORIDE 101	
Cr B 301	SILICIDES & BORIDES
Cr B 302	
Cr B 303	
Cr B 304	
4811 c	
CERAMIC 353	OXIDES
SILLIMANITE	
30% Cr-Al₂O₃	METAL / OXIDE BODIES
72% Cr-Al₂O₃	
52 Cr/13Mo/Al₂O₃	
NICKEL ALUMINIDE, 1505	

STRESS, X 10³ P.s.i

100 HOUR RUPTURE STRESS DATA AT 982 °C.
FOR CERAMICS AND CERMETS

FIG. 8.

5K 21074

STRESS, X 10^3 P.s.i.

100 HOUR RUPTURE STRESS / TEMPERATURE
CURVES FOR METAL-BONDED CARBIDES

FIG.9.

100 HR – RUPTURE STRESS DATA

A– SILLIMANITE
B– 30 % Cr–AL O₃ (OHIO)
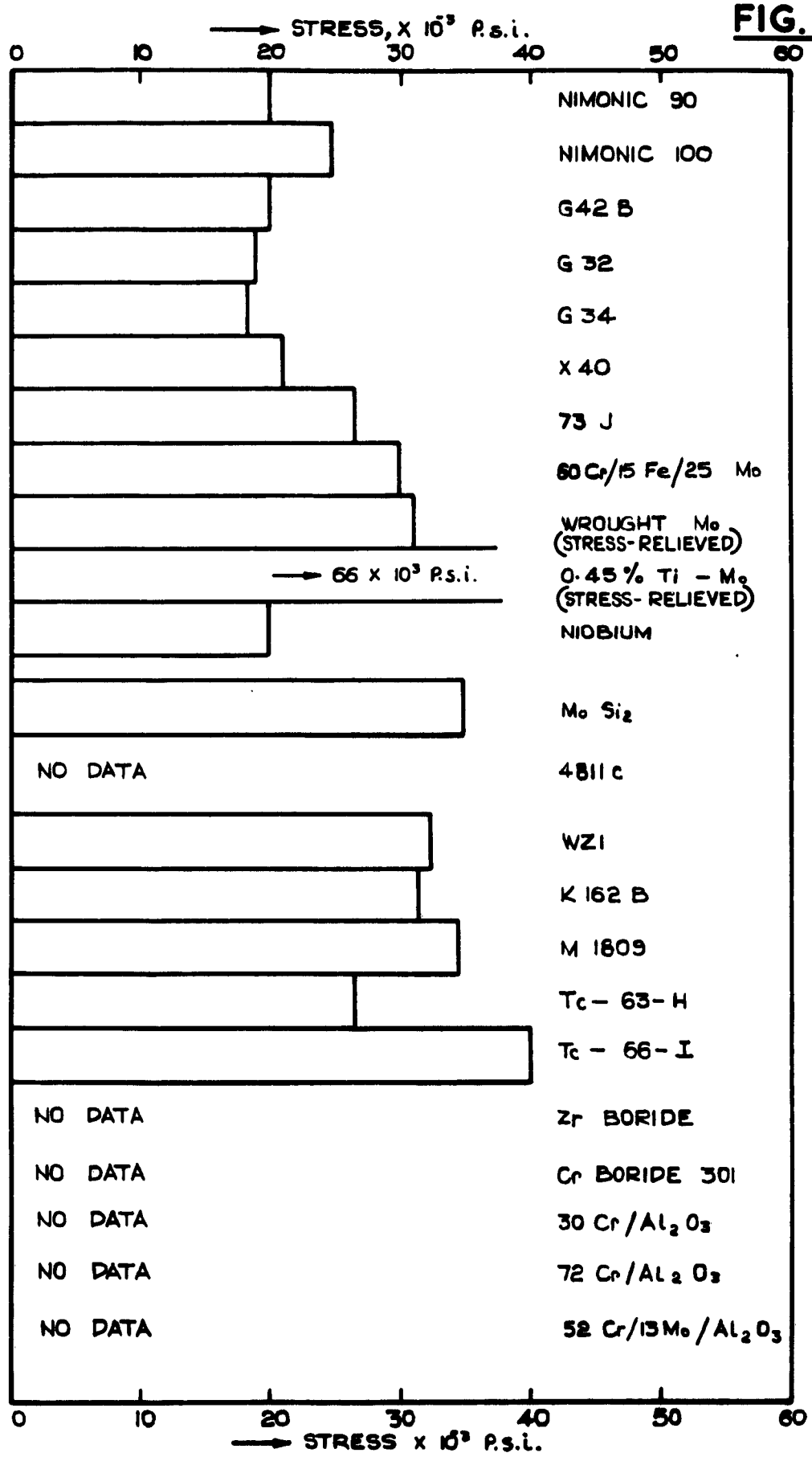C– 72 % Cr–AL O₃ (OHIO)
D– Mo Si₂
E– 52 Cr/13Mo /bal.AL₂ O₃

→ STRESS, X 10³ P.s.i.

→°C
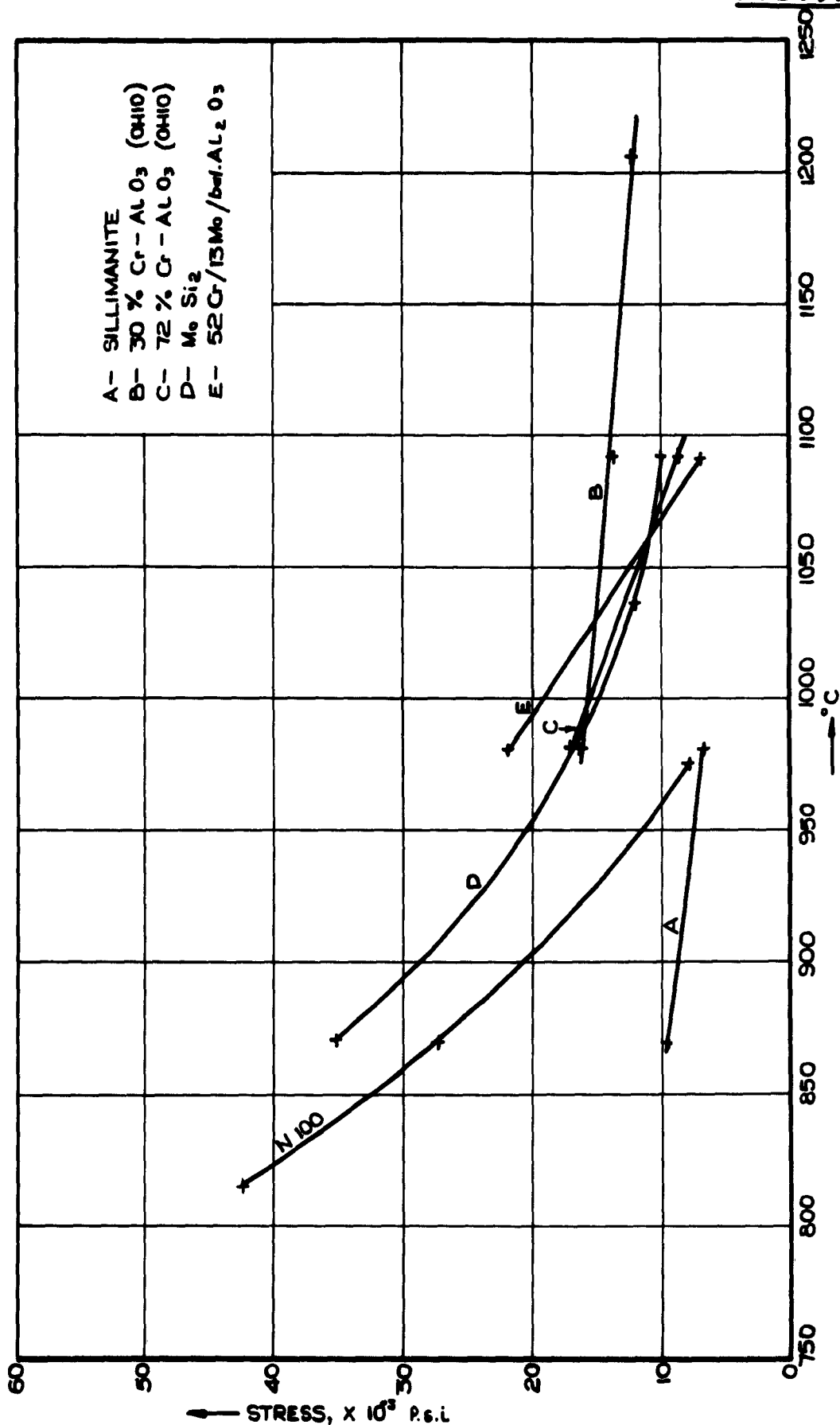
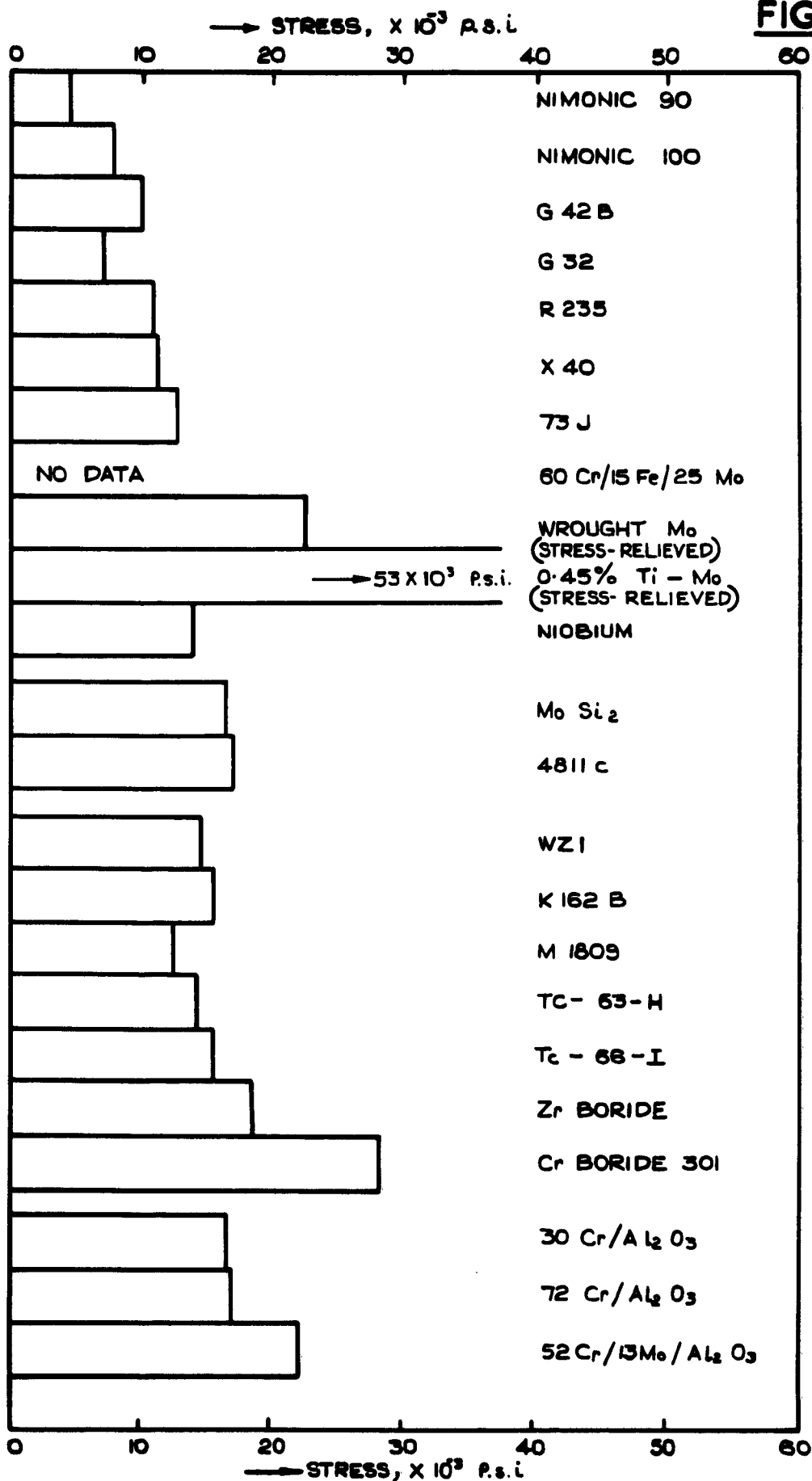100 HOUR RUPTURE STRESS / TEMPERATURE
CURVES FOR SILLIMANITE, MOLYBDENUM
DISILICIDE, AND ALUMINA-BASED CERMETS

FIG. 10.

SK 21076

STRESS, X 10³ P.s.i.

	NIMONIC 90
	NIMONIC 100
	G42 B
	G 32
	G 34
	X 40
	73 J
	60 Cr/15 Fe/25 Mo
	WROUGHT Mo (STRESS-RELIEVED)
⟶ 66 X 10³ P.s.i.	0.45% Ti – Mo (STRESS-RELIEVED)
	NIOBIUM
	Mo Si₂
NO DATA	4811 c
	WZ1
	K 162 B
	M 1809
	Tc – 63 – H
	Tc – 66 – I
NO DATA	Zr BORIDE
NO DATA	Cr BORIDE 301
NO DATA	30 Cr/Al₂O₃
NO DATA	72 Cr/Al₂O₃
NO DATA	52 Cr/13Mo/Al₂O₃

STRESS x 10³ P.s.i.

COMPARATIVE 100 HOUR RUPTURE STRESS DATA AT 871°C. FOR METALS, ALLOYS, CERAMICS AND CERMETS.

SK 21077

FIG.11.

→ STRESS, X 10³ P.S.i

NIMONIC 90

NIMONIC 100

G 42 B

G 32

R 235

X 40

73 J

NO DATA   60 Cr/15 Fe/25 Mo

WROUGHT Mo
(STRESS-RELIEVED)

→ 53 X 10³ P.s.i   0·45% Ti — Mo
(STRESS- RELIEVED)

NIOBIUM

Mo Si₂

4811 c

WZ 1

K 162 B

M 1809

TC— 63–H

Tc — 68 –I

Zr BORIDE

Cr BORIDE 301

30 Cr/Al₂O₃

72 Cr/Al₂O₃

52 Cr/13Mo/Al₂O₃

→ STRESS, X 10³ P.s.i

**COMPARATIVE 100 HOUR RUPTURE
STRESS DATA AT 982°C FOR METALS,
ALLOYS, CERAMICS AND CERMETS.**

COMPARATIVE SPECIFIC 100 HOUR RUPTURE STRESS DATA AT 871°C FOR METALS, ALLOYS, CERAMICS AND CERMETS.

FIG.13.

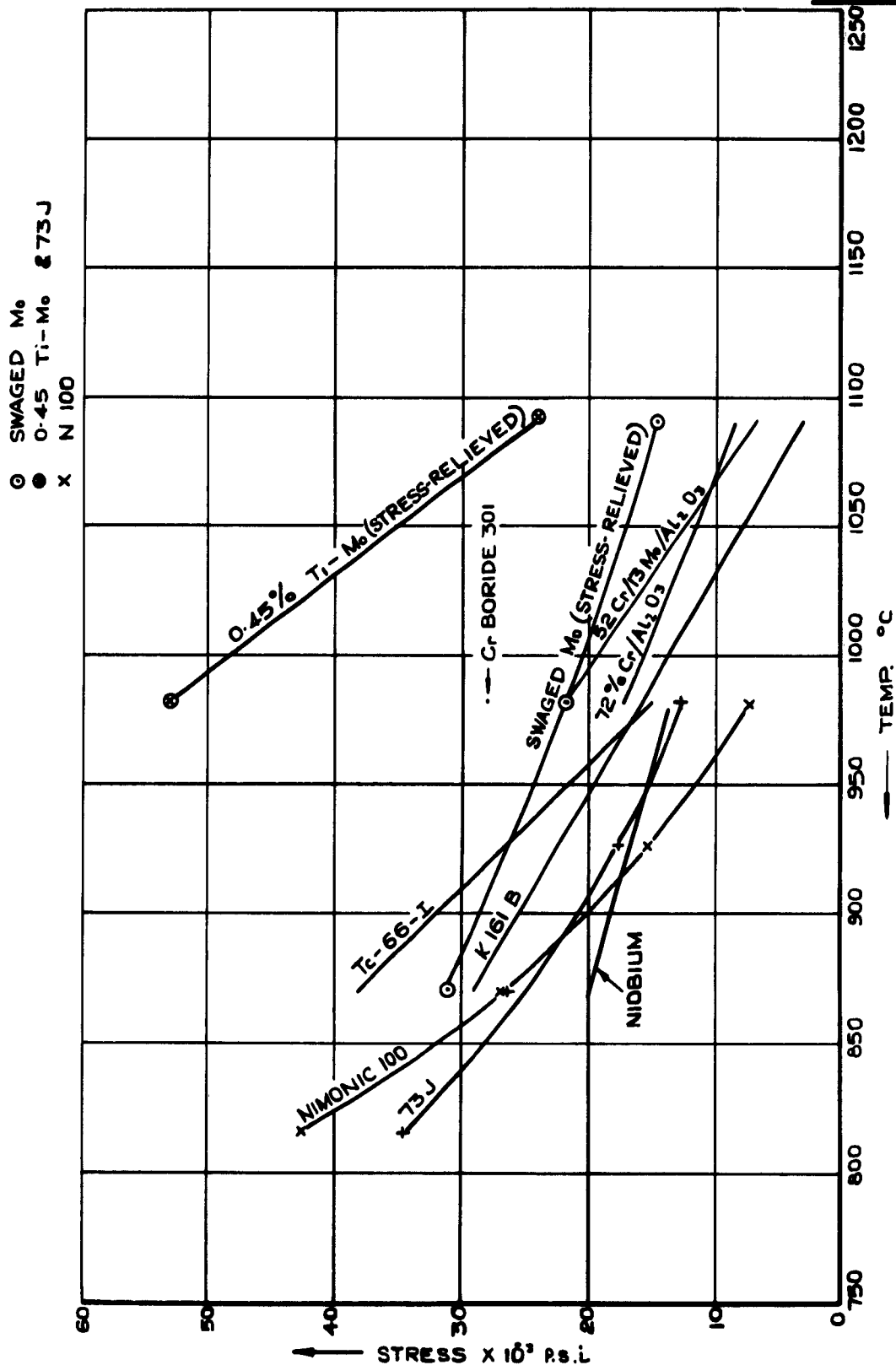→ STRESS, × 10³ P.s.i.

0 10 20 30 40 50 60

NIMONIC 90

NIMONIC 100

G 42 B

G 32

R 235

X 40

73 J

NO DATA   60 Cr/15 Fe/25 Mo

WROUGHT Mo
(STRESS-RELIEVED)

→ 43.4 × 10³ P.s.i   0.45 % Ti–Mo
(STRESS-RELIEVED)

NIOBIUM

Mo Si₂

→ 46.8 × 10³ P.s.i   4811 C

WZ1

K 162 B

M 1809

Tc – 63 – H

Tc – 66 – I

Zr BORIDE

Cr BORIDE 301

30 Cr/Al₂ O₃

72 Cr/Al₂ O₃

52 Cr/13Mo/Al₂ O₃

0 10 20 30 40 50 60

→ STRESS, × 10³ P.s.i

COMPARATIVE SPECIFIC 100 HOUR RUPTURE
STRESS DATA AT 982°C. FOR METALS,
ALLOYS, CERAMICS AND CERMETS.

FIG.14

SK 21080

COMPARATIVE 100 HOUR RUPTURE STRENGTH/
TEMPERATURE CURVES FOR REPRESENTATIVE
METALS, ALLOYS, CERAMICS AND CERMETS.

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1956.2
Glenny E.

**A REVIEW OF HIGH STRENGTH MATERIALS FOR THE
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A review and appraisal of data on metals, alloys, ceramics and ceramic/metal composites (cermets) in use or potentially useful for the rotor blading of aircraft gas turbines have been made. While it is evident that the existing nickel, cobalt and iron-based alloys, either wrought or cast, are unlikely to be useful at temperatures above 880°C (on a 100 hour life basis), no other materials immediately available are likely to replace these alloys for higher temperature service. Metallic alloys and cermets possessing similar or superior strength at higher temperatures have been developed but their inadequacy in other respects,

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e.g. lack of oxidation resistance (molybdenum-based alloys) and mechanical shock resistance (chromium-based alloys and cermets) precludes their application.

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